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TRANSCRIPTS OF THE PRESENTATIONS AT THE

WORKSHOP ON NDE OF ADHESIVE BOND STRENGTH

April 13-14, 1988

Orlando, Florida

Organized by:

The Nondestructive Testing
Information Analysis Center (NTIAC)
San Antonio, Texas

Sponsored by:

The U.S. Army
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This report is a compilation of the transcripts of talks presented at the Workshop on NDE of Adhesive Bond Strength. Included in the presentations are reviews of past and present efforts and capabilities. Also included are transcripts of discussions following the presentations.

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PRESENTATIONS

DISCUSSIONS

WORKSHOP ON NDE OF ADHESIVE BOND STRENGTH

The transcripts included here are taken from the presentations made at the Workshop on NDE of Adhesive Bond Strength held on April 13-14, 1988, in Orlando, Florida, in conjunction with the Spring Conference of the American Society for Nondestructive Testing. The Workshop was organized at the request of the Army Materials Technology Laboratory (AMTL) by the Nondestructive Testing Information Analysis Center (NTIAC) of the Southwest Research Institute in San Antonio, Texas.

The transcripts were taken from tape recordings made at the Workshop and represent the best summary of the meeting available. In some instances, the authors have provided figures they used with their presentations and those figures are included. In a few cases, segments of presentations were lost when recording tapes were changed. Otherwise, the transcripts are taken directly from the tapes and certainly contain a variety of errors. We believe that the transcripts will be of considerable value to those interested in the NDE of Adhesive Bonding and will help to foster continued improvement in the understanding and testing of adhesive bonds.

Information regarding additional copies of this publication may be obtained from:

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Our thanks again to those who participated in the Workshop and made it a success.

The NTIAC Staff

George A. Matzkanin
Nondestructive Testing Information Analysis Center (NTIAC)
Southwest Research Institute
San Antonio, Texas

OPENING REMARKS

This particular Workshop has been organized by the Nondestructive Testing Information Analysis Center (NTIAC) which is operated by Southwest Research Institute on a contract for the Department of Defense. Basically, the NTIAC operation at Southwest Research Institute is a forum, a gathering house, for information, documents, literature, and so forth, on the technologies of nondestructive testing. NTIAC maintains a computerized data base which can be computer searched for bibliographic information on specialized topic areas of nondestructive testing. NTIAC also engages in organizing forums for the dissemination of information in different areas of nondestructive testing and this is an example of one of those particular activities. NTIAC has undertaken a task to put together a state-of-the-art review or state-of-the-art report on the current situation regarding nondestructive evaluation and testing for adhesive bond strength and quality. Dr. Glenn Light from Southwest Research Institute has been heading up this particular activity and he'll give us a review on what he has found out from the accumulation of literature in this particular area.

The U.S. Army Materials Technology Laboratory requested organization of a Workshop on the subject of adhesive bond strength. There are second thoughts about using the word "strength" since there's some disagreement as to really what that is and if it can be measured, and what it means.

I'd like to introduce the first speaker who is Dr. Stanley Wentworth. Stan is in the Emerging Materials Division, the Polymer Research Branch at the Army Materials Technology Laboratory in Watertown, Massachusetts and one of his responsibilities is overseeing the Army's Adhesive Bonding Improvement Initiative.

Stanley Wentworth
U.S. Army Materials Technology Laboratory
Watertown, Massachusetts

OVERVIEW OF ARMY ADHESIVE BONDING IMPROVEMENT INITIATIVE

What I'll be doing here will be giving you some of the background as to how the adhesive bonding initiative got started, some of the activities that went on, and as we work into the presentation I'll be focusing more or less on the research aspects of the initiative since that's the area that I'm most familiar with and in which I'm working most directly.

I will give you some information as to some of the short-term problems that were encountered as well. Well, the fact that there are adhesive bonding problems out there is no news to anyone, but in terms of attracting attention at high enough levels to get something done about it, it takes sometimes a specific incident and the incident in case in point here and ignore that fact that says Marine Corp on it, had to do with an Army version of this helicopter which is the Cobra helicopter wherein a rain erosion boot on the leading edge of the fiberglass blade delaminated in flight causing a very significant aerodynamic imbalance in that blade and very nearly the loss of the aircraft. I'll give you a little bit better view of what's going on there. Figure 1 is a cross-section of the blade, this is the glass epoxy understructure here, on top of that is an electroactive coating that is there for enhancing certain electrical characteristics of the blade.* There is on top of that an epoxy primer, an adhesive carried by a glass scrim cloth and then finally this P0655 erosion boot itself which is bonded onto that assembly and it was the loss of that boot in flight that caused the problem. When that incident was reported up the line, the Commanding General of the Army Materiel Command, Col. Richard Thompson, indicated that a blue ribbon committee should be formed of people not directly involved with that aircraft to take a look at that problem and to see what the root cause might be and to recommend solutions to it. Well that blue ribbon committee on which I served part of the time went to Hunter Liggett Field in South Carolina and talked to the pilot and looked at the blade and Figure 2 is a schematic representation of what they saw on that blade. This whole region here is where that boot would have been and what happened is that it apparently lifted off up in this region and quite probably over a period of time, moisture infiltrated

*No figures are included with this transcript

there and that crack propagated out perhaps over a period even of months because there are these crack growth lines that show up here and then finally it failed catastrophically in flight and caused the problem that I mentioned. Well, the committee did report its findings up to General Thompson and he said that's all well and good but you haven't gone far enough. I'll bet there are problems in bonding out there with more than just aircraft so what I want you to do is survey all of the Army's major commands and this includes organizations like the Missile Command, the Tank Automotive Command, the Communications Electronics Command, as well as the Aviation Systems Command, hold a meeting of so-called experts to determine the root causes of these problems, and then formulate a plan of action which addresses solution of the current problems, needed research and development, establishment of a central data base, development of NDE, which is why I'm here, and to hold a Government/Industry Symposium. This last item was the Symposium that George Matzkanin mentioned that took place at Picatinny last fall.

A large number of bonding problems were identified by these major commands as you can well imagine there's an awful lot of equipment out there in a great spectrum of end use applications and I thought I'd just go through three of the examples which are more or less illustrative of the sorts of things that were encountered.

Example #1 is the Army's Patriot missile which is manufactured by Raytheon and the problem encountered here, the most serious one at least, has to do with the bonding of this ceramic nose cone to a Kevlar epoxy substructure ring that attaches it to the rest of the missile. The adhesive that's used here is a two-part epoxy which is cured at as close to ambient temperature as possible. The problem there being that there's a significant thermal mismatch between that ceramic material and the underlying composite structure and in order to keep from developing strain as a result of heat-up and cool-down of that structure, they try to keep it as close as possible to room temperature. Our first involvement at MTL with this problem was in fact to look at the entire cure cycle that was being used because it was found that there were problems in sustaining strength at the elevated temperatures encountered in the end use environment when this missile was in flight when the structure is bonded at room temperature. So we helped them there with some thermal analysis and some other analysis of the cure

cycle, came up with a cycle that seemed to be working at which point the manufacturer withdrew the adhesive from the market because it contains asbestos. This says currently qualifying a new replacement, that in fact has taken place, now a replacement has been selected and a cure cycle worked out for that. Things seem to be going along very well and the latest we hear that right now they're having problems at least in terms of batch-to-batch variation in that adhesive and there are problems with this system again.

Example #2 is the Army's Hummer, the high mobility lightweight wheeled vehicle which is a sort of generic replacement for the Jeep and 1-1/2 ton truck--it can be configured in a number of different ways--here you see it set up as kind of a weapons platform. The problem that we encountered here and it's sort of instructive in terms of the kind of attention that these various commands paid to our solicitation of problems, had to do with the bonding of the data plate to the dashboard in this vehicle. The problem was that they were bonding it to a polyurethane painted surface and this is the classic case wherein not enough attention is paid to surface preparation to get adequate bonds. The solution in this case works--they use rivets.

Example #3 shows a more interesting problem which has to do with this lightweight field deployable bridge. But this is a concept developmental item now that will make heavy use of composite materials in place of the conventional metal that has been used for this application in the past, the idea being of course to lighten that structure so that it's more deployable and perhaps also for a given weight to be able to bridge a larger gap. One of the joining techniques being considered for this item is adhesive bonding. The designers of that system have developed this wish list of characteristics for an adhesive for this application. They would like to have a 10,000 psi lap shear strength in that adhesive, they would like it to cure at ambient temperature and that's especially important for the field repair aspect of this item. It would be very desirable to cure this out in the field and not have to bring it back and put it in an autoclave, should be inert to moisture and have a 15-year service life. Well, if someone can come up with that adhesive, let us know about it because that's the answer to a lot of prayers. But it does indicate the kind of long-range needs that came out of this study as well.

So as I said, the problems that were identified fall into two categories, the current problems on existing systems which require the short-term solutions and the future needs of the sort that I just mentioned requiring mid- to long-term solutions. For current problems, and this is probably not news to anybody, the overriding root cause of this is not a fundamental lack of knowledge on how to do this kind of operation, but the failure to do it effectively and properly and consistently time after time. Failing to consider any or all of these points--the joint design which includes a consideration of the environment in which that joint is to operate and that means the natural environment (temperature, humidity) as well as the operational environment, operational fluids for the Army, for the Military, perhaps even the effect of chemical warfare liquids on that kind of a structure. Selection of the adhesive is often a very casual thing wherein the person who makes the selection is not necessarily an expert but he knows more than anyone else in the shop making the selection. Process control and quality control: these bring in at least to some extent the issue of nondestructive evaluation. These things are not treated sufficiently carefully. For instance, in my role on that blue ribbon committee we went to the manufacturer of that helicopter blade and in the storage area where the adhesive components were being stored right beside the resin drum was a 5-gallon container of silicon release agent. The juxtaposition of those two materials in the same area is just anathema to good adhesive bonding practice.

The solution to these problems was for each of the major commands to select a specific problem area and based on the information developed during the study wherein the problem causes were highlighted to go back and look at that particular item, come up with some solutions, develop a model program to address these deficiencies and using that model then to apply it to the rest of the equipment within their purview which makes use of adhesive bonding. This activity is in process now and in fact we have a compliance review as its called by our higher headquarters scheduled for late summer to see what progress is being made by each of these commands on their particular problems.

Research and Development Program

The future needs require the development of new knowledge and are addressed by a program of research and development covering the topics of chemistry, surface science, and mechanics. And its the essential nature of adhesive bonding

and adhesion science that it's a very strongly multidisciplinary area represented schematically here and also you'll see as I talk through this that some of the terms are used almost interchangeably but it's useful to consider that adhesion science is, in fact, the synergistic overlap of these three fields and one of the problem areas in the past has been that people in each of these fields tend to talk to their own people without having an appreciation of even the language let alone the needs and problem areas in these other fields. We're making progress in that area and that was one of the reasons for that Symposium at Picatinny last fall. Now in this plan we address each of these topics individually but again they overlap. Under the area of chemistry, there's the need for new adhesives, there's the need for new surface preparations, and there's the need for surface preparations for newly emerging materials and I'll get into that in just a bit.

In the area of new adhesive development, many of the things that I mentioned for the lightweight bridging are what's needed. We need more, or increased, shelf life, improved strength, improved durability, and also more and more these days improved thermal resistance. In an effort to lighten the force, more and more we're going to the replacement of metals with organics and the closer you get to energy sources be they rocket thrust motors or combustion engines or for missile applications perhaps out on the leading edge of a fin or something like that, you need that improved thermal resistance. Now the program that we have in place and ongoing addresses at this point primarily that last issue. I know most of you are not chemists here so I'm not going to go into much detail here. Suffice it to say that we believe that we can improve the thermal resistance of certain kinds of high temperature resistant polymers through the inclusion of more thermally resistant component links. This molecule here has a major virtue in terms of thermal and thermal oxidative stability, it contains no hydrogen. So if we can incorporate that into the backbone or use it as a cross-linking site on a polymer, we can probably significantly enhance its thermal oxidative resistance. The objective as I say was to enhance the thermal oxidative and thermal mechanical stability, the idea was to introduce control cross links through the use of this molecule and progress has come significantly farther than this now. In conjunction with the principal investigator, Tony Zienick at Ohio State who has prepared the polymers, we have done thermal analysis evaluations of these materials and some of these look quite interesting. Some of this work has been published in the Journal of Organic Chemistry.

Another area that we're looking at for improved thermal resistance for adhesives is in the area of polyphenylquinoxaline chemistry and the idea here is to prepare so-called isomers of this bulk basic polymer with the idea that these ionic sites can serve as virtual cross links and enhance the thermomechanical stability at elevated temperatures. This is a program essentially concluded now at Rochester Institute of Technology with Professor Eric Moskala* and student doing the work. Unfortunately that program has not been very successful--we feel that it is still worth pursuing and will probably try to continue that within our own laboratory.

New surface preparations--seems like there are always needs for new methods to prepare surfaces for adhesive bonding. This is the most crucial phase of an adhesive bonding operation--the preparation of the surface prior to the application of adhesive. It's probably pretty well worked out for aluminum at this point such that when the best procedures are done right you get strong durable structures that give you what you expect from them. But titanium is a problem area, bonding to steel is a big problem for the Army, we've still got an awful lot of steel equipment out there and the bonding to organics is becoming increasingly important. Much of the Army's work in this area has been conducted over quite a number of years now at Picatinny Arsenal or the Armament Research Development and Engineering Center in Dover, NJ. It's a long-standing program that's accomplished a number of objectives over the years. There's a tremendous data base available on the specific bonding problems--bonding substrate A to substrate B to experience certain kinds of conditions, what kind of adhesive do you use--that kind of information is available at Picatinny.

Bonding to oily steel has been a program there to evaluate commercial products which are touted as being useful for this application. Again this is very important to the Army because there's a lot of steel used in the Army and if you can bond to it without doing rigorous surface preparations, so much the better, it's a lot less costly that way. The P2 etch is an outstanding accomplishment in my view. It is a real valid example of transfer of technology from a federal, in this case an Army laboratory, to the private sector. The P2 etch is a surface preparation for aluminum that avoids the use of chromium which is as many of you know a serious environmental pollutant and the very good example of the utility of this process which was developed at Picatinny is down

*actual spelling may be different than shown

here in South Florida at Piper Aircraft where for five years this process has been used in place of the chromate etch to prepare aluminum for bonding in this aircraft application and they have used it effectively without problems--it works.

The bonding to polyolephins which is an area of increasing importance--there have been procedures worked out at Picatinny for the preparation of surfaces of these materials for bonding.

FY87 program it says here, in fact since the '88 money was just transferred last week, most of these things are still ongoing. You can see here a real focus now on the organics. It's very clear that that's one of the ways the Army's going to lighten the force. And so this program that looks at the bond durability to rubber and looking at the materials shown there, bonding to engineering plastics, Corlon*, Norell*, that class of material and bonding to composites, a little bit more to say about that in another context in a bit but composites are more and more important to the Army and joining by adhesive bonding is an important option.

Also under chemistry but perhaps equally under surface science is this topic of surface preparation for new materials and these are the kinds of things we're talking about here--the metal matrix composites, emerging materials, thermoplastic matrix composites and also the lithium aluminum alloys which are becoming available now. We have a couple of programs going on in this area. Adhesive bonding of metal matrix composites is a joint program at the University of Lowell with Professor Steve Petrie* and Paul Burkwist* in our labs who is in fact doing this as a masters thesis program. It's objective is to determine whether or not the techniques used to prepare standard aluminum for adhesive bonding is adequate or appropriate for metal matrix composite materials. Metal matrix materials are metals like aluminum that contain reinforcements just as fiber resin matrix composites do. They can be fibers or in the case that we have selected to look at here they can be particulate reinforcement in this case silicon carbide as you'll see. We have selected this particular material to look at, some of this characterization has now been completed. We've selected this particular material and we've found as time has gone on that we're going to be focusing on the 30 and 40% loading level in the 6061 because of its availability

*actual spelling may be different than shown

and its potential use to the Army. Preliminary studies have indicated that we're probably going to rule out this room temperature curing adhesive there. We have some problems getting void free bond lines there, more to the point, that kind of a material just does not develop the strength that seems compatible with an advanced material such as this metal matrix material. So we're going to be focusing on a 250 degree cure film adhesive which we haven't finally selected yet.

A bit of an update--we have received free samples of some of these materials and done a screening of the various kinds of surface treatments and looked at the surfaces produced. What we have seen is that the surface is significantly enriched in silicon carbide particulate and we feel very strongly though we do not yet have the evidence that this is going to have an impact on both strength and durability. This is a scanning electron micrograph of the 30% material that has been treated with the so-called FPL, a chromic acid etch. There is a lot of particulate here. This for instance is known to be a particle of the silicon carbide and scattered all through this area there's a significant enrichment at the surface that's not just aluminum oxide on that surface. The evidence for that is this is mapping of that surface for silicon using the EDAX attachment on the scanning electron microscope. These light areas show the occurrence of silicon--silicon of course is in the silicon carbide so you can see that this whole area here is just almost entirely silicon carbide. A very quick and dirty crude test, I asked Paul to just take a piece of adhesive tape, put it on that surface, lift it off, see what came off. This is what came off. This is off of that surface very similar to what you just saw and this is in fact the surface of the tape, these areas in here are the tape that's out of the focal plane. Very ready removal of this particulate material from the surface and again the silicon mapping for silicon here strongly supports the fact that that's all silicon carbide. Clearly that's going to have an impact on the strength and most likely the durability of joints to that surface. So that program is ongoing. We're about to start the bonding studies on the metal matrix material and we'll shortly begin the durability phase of that program.

The other program which we have ongoing in this area is the adhesive bonding of thermoplastic matrix composites funded by us at Imperial College, London,

under the direction of Professor Tony Kinloch*, the work being done by Mr. George Kidokian* with us supplying some of the materials. The objective is to determine the feasibility of using adhesive bonding to join thermoplastic matrix materials and the kinds of things that we're especially interested in here is the so-called peek material which ICI in England is now strongly supplying as a commercial product and has a lot of advantages for use by the military and also the Phillips Ryton* graphite fiber reinforced material and the program addresses the issues that you see here using state-of-the-art epoxy adhesives. Several materials have been screened, there has been strong evidence that if you just take that material as supplied or doing just a cursory kind of surface treatment, you do not get effective bonds to that surface; however, it's been found that a corona discharge in air provides enough functionality and/or roughness on that surface that good joints can be formed to it. So there are problems, but there appear to be solutions as well.

Now in the area of surface science, the plan identifies three areas where work needs to be done. In the area of micromechanics, ion implantation and interphase studies. Very little to say about these first two. Micromechanics is essentially doing mechanical testing in something like a scanning electron micrograph so that you can see in real time what is happening at that microscopic or submicroscopic level. We feel that a lot of information can be gained by observing those processes. Ion implantation may not be practical because of the hardware cost for surface treatment for adhesive bonding but there are reports in the literature that for instance the surface of platinum can be enhanced in terms of its bondability by I believe nitrogen atom bombardment and implantation. The area of interphase studies is we feel perhaps the most crucial area of work in all of adhesion science. The interphase is the region of an adhesive joint between the bulk of the adherend, its surface layer which for most metals will be a layer of oxide, the adhesive that's in contact with that will have its own segregation in composition because the surface oxide layers are physical chemically active and then you have the bulk of the adhesive itself. This is a crucial area for an adhesive joint because that's where it happens, that's where the loads are transferred, if you have problems, that's almost always where they occur. We have an inhouse program that addresses this issue being conducted by Walter Zukas*. Its objective is to test the postulate that adherend surfaces such as the aluminum oxide on the surface of aluminum can perturb the chemistry

*actual spelling may be different than shown

of the adhesive cure. It's not unreasonable to think that this may be the case because aluminum oxide is the alumina that is used in column chromatography for separating organic molecules from each other. So there could well be some influences on the composition, the stoichiometry therefore and the structure of the cured adhesive. This program is addressing that and we're using model surfaces if you will, finely ground alumina, probably look at finely ground glass and maybe some other metal oxides to see what effect they have on the course of the adhesive reaction chemistry and we're probably going to end up looking at some model compounds here so that we can isolate them, do spectroscopic analysis and determine the actual molecular structure of the cured species here to see how that differs from the unperturbed cure.

In the area of mechanics, I don't have much to say about most of these except this first one. Laser interferometry is a technique that has been indicated to me and I'm not an expert in the area of mechanics at all as being a useful way to watch how an adhesive joint fails in real time, say in an Instron machine or something like that. There's a strong need for test method development. The lap shear test is not a good test for screening and evaluating adhesives. It's used almost universally because it's essentially the simplest adhesive test to use but it does not provide good information about the bulk properties of the adhesive, there are lots of problems with that joint--geometry, there are peel forces introduced at the edge for instance, there are cases I believe where if the results of an evaluation based on this test are used to select an adhesive, and then that adhesive is applied to a particular more complex loading situation, it turns out that other adhesives would have done the job better than the one chosen using that method. And for the military there's also interest in the effect of ballistic impact on or near an adhesive bond on the overall residual strength of that. This starts to get back to the NDE area again.

Predictive models for improved design of adhesive joints--that's a narrowly focused program in our lab now but it's an example of what I feel is probably the ultimate objective of adhesion science and that is to provide computer models so elaborate, so sophisticated, and so global that they can give you a very good prediction of the entire service life of an adhesive joint. That will help in the design phase and it will help very strongly in monitoring the overall life

cycle of such a joint. These would in all likelihood be based on finite element models and those models would include in addition to all of the mechanical loads and bulk properties of the constituents that go in. Perhaps eventually things like kinetic expressions for degradation reactions when those are known and understood, expressions for the diffusion of moisture which is the single most critical factor in the degradation of an adhesive joint over time. We're just beginning to crawl here, there are models that are beginning to pick up issues like this and I think Professor Brinson this afternoon may have a bit to say about that.

The database in NDE--one of the tasks under our initial mandate from General Thompson was to enhance and upgrade the database that exists at PLASTEC at Picatinny Arsenal. The idea here is to just expand it, make it more user friendly, more it more generally available to the user community, and also to incorporate into it some of the lesson learned perhaps as a result of the initial study that we did of the problems and over time as more and more examples and solutions to adhesive bonding problems come along so that everyone doesn't end up reinventing the wheel every time there's a need for it. Here, of NDE, I'm not going to say much about this topic except to indicate to you that we feel this is one of the strongly pacing problem areas in the area of adhesive technology. We would like to have quantitative NDE and by that I mean putting numbers on bond strength. That's going to be a key issue in probably most of the discussions here for the next day and a half. It's not clear whether or not that is possible, it's my belief that if it is, it probably requires some new science, some fundamentally new insights and ways of interrogating what's going on in that interphase region because that's where the strength and the durability comes from.

And then finally, one of the mandates was to review the current military specs and standards that deal with the use of adhesive bonding. The idea is to update them, reflect state-of-the-art in materials and processes and to produce handbooks as appropriate. In fact one of these was in process at the time the tasking was given and it has since issued. I believe this document may be available through our Specs and Standards Group at AMTL; if not, they can tell you how to get it if you have an interest in this area. But this is a quite recent volume as you see; unlike most MIL specs it's probably as good as it gets

in terms of this kind of document. Well, why all this emphasis on adhesive bonding? There's a whole litany of reasons one cites for the use of adhesive bonding versus other joining techniques; light weight--if you're not using mechanical fasteners you're not adding weight to it; for large areas it's an effective way of transmitting a load over all of that area and having the entire structure be load carrying; a good resistance to corrosion; and especially good fatigue which for aircraft applications especially is an important consideration. But basically it has to do with things like this. This is one of the prototypes that came out of the ACAP program, the All Composite Airframe Program. You can see that there is heavy use of composites throughout here; you can probably even guess as to what some of those materials are just by the coloration. But to me if the Army starts putting all of these things together using rivets, we have stepped significantly back from the leading edge of technology.

Paul Kenny
U.S. Army Materials Technology Laboratory
Watertown, Massachusetts

OVERVIEW OF ARMY BOND INTEGRITY NDE PROGRAM

I'm the Principal Investigator for the bond integrity NDE program. It was originally called bond strength NDE program but we had trouble with that so we changed that name. We originally called this Workshop the bond strength NDE Workshop and so because of all the information that went out, we didn't really have time to change it so you didn't think there were two workshops going on. The Workshop that we're all at right now is an element of the overall bond integrity NDE program and it is an offshoot of the Dover conference held last November in which Stan Wentworth played a big part. The increased emphasis on structural adhesive bonding in the Army began when General Thompson said there would be a technology thrust in the area. A lot of money was put into this very rapidly and a lot of projects came on board. Among other things this thrust was to address one of the root causes of adhesive bonding problems and that is to perform adhesive bonding operations properly and the bond integrity NDE program was developed to support this technology thrust. The goal is to establish and improve NDE techniques to assure adhesive bond integrity in Army structures.

A two-pronged approach is being used to achieve this goal and that's implementing existing technology and developing a bond strength measurement technique. Of course, I'm not sure exactly what that second one means at this point but that's something we can discuss in the next day and a half. Adhesive bonding is as critical to the Army as it is to everybody else here and its application requires intricate process controls including material selection, adhesive selection, and the control of the bonding conditions. Faulty execution of the bonding process is possible because of the large human element involved. Thus the user must apply stringent acceptance tests and that can only be done via the nondestructive testing of all bonded parts. The ultimate aim of a nondestructive test is the correlation of some parameter by nondestructive methods with the failure property of interest. This failure property is complex for bonded joints where quality is affected by both the cohesion and adhesion. Presently, the quality control of adhesion is only possible prior to the application of the uncured adhesive. There's no nondestructive test that's yet

been developed to correlate with intermolecular forces at the bond line. So to adjust these issues, we have the following program objectives which are to provide more effective production control over process variables and product uniformity associated with adhesively bonded structures and to implement the above via the generation of procedural documentation for process control.

The bond integrity NDE program plan consists essentially of these elements listed here as well as other efforts that are not directly under the program but with which we do have influence over.* I'll briefly describe these projects, what they're all about and we can use that as a springboard for the rest of the conference. I'll talk about the last of these first--that's this Workshop we're at right now. Again, it's sponsored by NTIAC through MTL and it's a follow-on workshop to the Dover symposium. The goal of the Workshop will be to extend the topic of NDE beyond the Dover conference and we'll focus and summarize in the current state-of-the-art in NDE of adhesive bonding and hopefully provide guidance for future thrusts.

The NTIAC special task is a project entitled Evaluation of Bond Testing Equipment for Inspection of Army Airframe Composite Structures. It's objective is to evaluate presently available bond testing equipment and to obtain more reliable detection of delaminations and disbonds. It expands the scope of an Air Force project which used F16 reference samples to evaluate the bond testing equipment. The present project used real samples off of real aircraft in order to evaluate the bond testing equipment. Results indicate that it can be determined in some equipment as more appropriate than others depending upon the particular bonding scenario. We should have Hegeon Kwun in the audience and he's the one who did perform the work. If you have any questions about that particular project, you can go to him.

The Aero Summer Faculty program is one that isn't directly funded through us but is does bring in a university professor over summer break to MTL and we're using that every year of the program that we can possibly get a professor and we have picked one up and hopefully Dr. Joshi is here today. He's been picked up for this summer and he'll be working with us for about 12 weeks. We'll be working on topics of mutual interest there.

*No figures are included with this transcript

The Small Business Innovative Research Program is a special pot of funds that can be used to award contracts to smaller firms. We've awarded a contract to Bio-Imaging Research which is applying computer tomography methods to bonded specimens. The SBIR program is a multi-year funding program subject to a review after a 6-month Phase I effort and hopefully each year we'll pick up a new SBIR program so that we kind of have some overlap and we have a number of ongoing efforts. The bond line characterization is a project which is entitled Using Low Velocity Impact for Quality Assurance of Adhesively Bonded Joints. It's a contract whose goal is to develop a reliable method for assessing the structural integrity of bonded structures. This is work being performed at the University of Oklahoma by Ron Kline who presented some of this in a talk he gave yesterday and again, we can direct some questions toward him if you'd like. I think that would be appropriate.

The bibliographic searches have been generated by both NTIAC and PLASTEC and information extracted from these indicates that there's a "ton" of information out there. The searches are probably about that thick. Those searches among other things are being used for the state-of-the-art report or SOAR that Glenn Light and Hegeon Kwun are going to be talking about later, I believe this morning. Both the state-of-the-art report and the Workshop we're at now are primary efforts that are being used to implement existing technology.

The test specimens that are making the rounds for a number of these efforts are the F16 reference samples which are intended as one-sided ultrasonic testing specimens. They were used by NTIAC with the Air Force special task they had which is the precursor to the special task that we have here using the real specimens. They are also being used by the Idaho National Engineering Labs where they're using acousto-optic methods and Dennis Kunerth I believe is going to be giving a talk today on some of that work. Other specimens used are the real aircraft specimens which are being used by NTIAC for this special task as well as by Bio-Imaging Research on the SBIR project they're working on. The data acquisition equipment is equipment that has been and is being procured by the NDE group at MTL through data analyzers, ray processors, and some more computers and all this equipment's going to be used to support in-house work by the NDE group and right now current work is focusing in on some feature scans and B-scans which would be a slice through a part looking head-on at it.

I'll be here to discuss any of these efforts with you afterwards if you'd like. Again, many of the PIs are here and we'll have a number of these discussion sessions here in order to look at this a little more thoroughly and it might be appropriate to address your questions with them or me depending on the questions you might have. From here on in let's just have ourselves a productive workshop. Thank you.

Robert Y. Ting
Acoustic Materials Branch
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Orlando, Florida

ELASTOMER-TO-METAL BONDS IN SONAR TRANSDUCERS: THE PROBLEM AND SOME NDE ATTEMPTS

I'm in materials R&D, I'm not too familiar with NDE and so this is a very new community for me. I'm with the Naval Research Laboratory, which is headquartered in Washington, DC. NRL has 15 research divisions and all of them are in Washington except the Underwater Sound Reference Division. Several years ago an Admiral said you guys down in Orlando ought to be called a detachment. So now we're a detachment.

I have an acoustic materials branch in which we're concerned with all the materials problems in underwater acoustic systems, so this morning I'm going to just tell you a little bit of our interest and what we have done in relation to adhesive bonds. We have worked with the Office of Naval Research through their Center for Adhesive Science at VPI. I understand Prof. Brinson is going to be on the program later on. We work with a variety of Universities, such as the University of Cincinnati, Lehigh University and also contractors like Texas Research Institute etc. I understand Dr. Bar-Cohen will be here on the program later on as well. So, what I will do this morning is just tell you the kind of problems we're facing and the very preliminary NDE attempts through internal work we have done. This is a cut-away view of the 688 class attack submarine and you notice in the front, this is the sonar dome bow structure area and the main eye for the submarine is this 15-foot sphere sonar structure and on this big sphere is mounted many sonar transducers and is used for communication detecting and active sonar operation.* Each of these little holes here represents a sonar transducer, is designated as TR317 or a previous version called TR155. Basically, this thing sits about this big, weighs about 80 pounds, it has an aluminum head mast here with a piezoelectric ceramic stack as the motor. So when acoustic energy comes in from far field it causes the head mast to oscillate and generate a voltage by the piezoelectric ceramic stack. Or more importantly, under active drive the high voltage will be applied to this ceramic stack such that the head mast will be vibrating at the specific acoustic frequency you desire and dump that acoustic energy into water, so this is how the device works.

*No figures are included with this transcript

Now the problems for this high voltage electroacoustic device--you want to maintain the watertight integrity and what you have is just a layer of rubber bonded to this surface and that is the protection and this is the bow I'd like to talk to you a little bit about this morning. What you see here is inside a sonar dome. Inside a sonar dome on this sphere you see these transducer face now is a rubber face. This transducer is mounted inward into this spherical structure and bolted down by these four bolts. Here is the steel structure, here is the zinc box for corrosion protection. The first picture you see is that there's a lot of corrosion there. The sonar dome is freely flooded and it can be so dependent on where the boit has been, it's exposed to everything--in the Bahamas or in the North Pole the temperature variation, the bolt will go up and down so there's a pressure effect and depending on where it's docking, there's a lot of change in water salinity and the pH and so forth. Jt's a very, very tough environment and for these devices or for these bonds you want it to last for 15 years. And it's a very, very difficult job. When the boat comes in they will pump the sonar dome dry and then the technician will go in and do a insulation resistance measurement of each of the transducers. This one failed our test so we put a tag on it indicating that the transducer will be pulled out and sent to the transducer repair facility in the shipyard for repair.

Well, let's look at the transducer more closely in this case on the side. What you observe clearly is that there's corrosion, there's a crack, so the rubber is not bonded to the middle substrate anymore. Furthermore, the rubber face is not flat as it's supposed to be; instead it has bulged out. What it means is that the water has gotten in when the boat was down there. When the boat came up, the pressurized water pushed the face outward and if you take that transducer back into the shop and look at it, you can easily poke (the face) aside with a screwdriver and see this kind of thing. Namely, the rubber bond to the metal has failed.

Schematically, this is what the headmast looks like. Here's the shroud which is just a little can made of mild steel. Here is the aluminum block, so the rubber is molded to the front and into this annulus region. So this is the bond in which we've seen a lot of failures. Basically there you have the metal substrate, on the oxidized metal surface you first apply a primer, then apply the adhesive. Basically what the Navy has been using is a Kemlock type system and

then you mold the rubber, in this case Neoprene rubber, to it. So you have a lot of interfaces, you have different type of material and then surrounding it is water of all kinds.

Another example is some of the rubber we molded directly to piezoelectric ceramic elements. So what you see here are two ceramic cylinders, PZT type, lead zirconiumtitanate type ceramic rings. We apply the adhesive then mold the rubber as an encapsulant to protect it from water. In this particular case when it has failed, they cut it open and you can see that there's a lot of failure of that adhesive bond. What's the impact of this type of failure? Well, the first kind of transducer, 317 or 155 type transducers are supposed to last 15 years. Instead, 100% of them failed within 36 months. The population's like this. Hardware for each of these units costs about $3000. On that one sphere you round off, say there's a thousand elements, that's 3 million dollars of hardware. In addition, there's installation, repair, and the boat is tied at the dry dock and can not be operated and so we're talking about millions and millions of dollars here of different types of transducers.

The problem is very, very severe and so starting about 5 years ago the Navy has put a lot of effort into trying to improve the rubber, the surface preparation, the adhesive system and the durability study. This is where the more concerted effort has come in.

The last item here is the sonar dome rubber window. There are about 100 or so in the fleet and it's been failing one after another. This picture here shows the sonar dome rubber window for surface ships. It's a very large rubber structure in which steel cables are used as a reinforcement in order to get the mechanical strength. The system is internally pressurized, fill water pressurized in order to maintain the contour. As you see by these numbers here it's a very, very large structure made in two pieces by B.F. Goodrich. To give you an idea of the size, here is a man standing next to it. The lay-up is made in Akron, then these things are flown by C5A to Long Beach, California, and then a very large autoclave is used to do the fabrication. Well, because of the manufacturing technology--you can see here one of them--the dome tends to burst or rupture toward the center where they have a specific splice design. Once this thing fails, it's a big headache. The last one I heard was the USS Virginia--it

failed in the South Indian Ocean. Once that thing fails, it stops and of course the water got in, all electronics were lost and it just went down the drain. The worst part is that the boat has been towed backwards, in that case back to the Philippines and then a dome replacement had to be flown from California to the Philippines for a repair so there's a lot of cost involved. Here it gives you an idea of the different plies, it's a cut view of a portion of the dome, you can see the transverse plies with a steel wire coming out or longitudinal plies with a steel cable lying in this direction. Because of the hand layup there are cavities left in there and also the red colored area means the bond just wasn't sufficient at all. When water permeates through the rubber it eventually got caught in this void area and then slowly crawled away from the steel wire and then the structure lost its strength.

So you see the magnitude and complexity of the problem so some of the NDE attempts have been made with these different techniques. I assume that most of you are fairly familiar with it and I would not go through with them. I understand one of the papers in the other session talked about leaky Lamb wave techniques.

Now I just want to show you basically the kind of results that typically we have seen. This is the head of that TR317 transducer I have shown you. Basically, here is that aluminum headmast. This is the shroud with the four bolt holes and here is the annular region where the rubber will be molded into, as well as covering the whole face. In this particular study, what they have done is to introduce artificially the debonded area of specific size, 1/8 in. all the way to 3/4 in. in circular form. And they mold a transparent polyurethane rubber over the face as they would in molding a rubber so that they can see these things. Then they stress this bond surface and place it under different vacuums so that the debond area may be enhanced under holography and so they see this kind of test result.

They count the dark fringes around these things and compare what the physical dimensions should be under different kinds of vacuum levels. These are in inches of mercury and you get to this kind of data. And you correlate that to the actual dimension with respect to the measured dimension. Ideally you will get something like this but this is the kind of data that has been obtained so far.

This is one of the sonar dome rubber window panels that steel wire reinforced the Neoprene structure taken from the SS Radford. On that particular ship, the sonar dome was ruptured and then the worker went in and repaired it and it lasted for another year or so, less than two years, then eventually they replaced it with a new dome. Then the repaired old dome came off, they cut off into different panels and use it as a test piece with different types of NDE measurement. In this case, a 39 in. by 39 in. square panel--in this panel they have determined the specific void of bond weakness in the structure so using an ultrasonic C-scan technique they were able to identify this void structure and also two of the repair regions here. However, the ultrasound also gives an anomaly signal in this area which they couldn't find with any other technique any of the problems in the structure. So the ultrasound seemed to offer some promise yet in the other area gave you a problem.

This is a shearographic record of that same piece of a panel. You notice that the long voids are clearly identified here and also you seem to have identified some kind of the repaired rib seams on the back of the dome along this region. So that technique seems to offer a certain promise as well. The leaky Lamb wave technique basically is to consider the test piece of some sort, say an adhesive bond as a thin plate and then you have both the symmetric and unsymmetric wave coming down in this thin layer and if there is an unbonded area presumably the Lamb wave will provide some leakage so if you have an acoustic arrangement of this sort in this domain at the right frequency you will detect some of the inner flaws. I think this is the basic premise of Dr. Bar-Cohen's work with TRI. So they have used a specimen like this. It's a panel and they masked off all this specific area and then bond it and try to detect this debond with the acoustic arrangement they have. In a single scan across the plate you will notice that in the bonded flawed area indeed you see a 3 1/2 dB energy leakage there, in this case about 4 MHz. However, though you'll notice the leakage indication here and this particular signal went away when you go to different frequencies.

This is a very poor reproduction of a color photo Dr. Bar-Cohen had and this is the ordinary ultrasonic technique; you will see that in this debond area. What you can see is fairly minimal, seems that with the leaky Lamb wave they could get more indication or more diagnosis for the debond area. However, you

also see a lot of things in the background which was attributed to the anisotropy or the homogeneity in the material. So we see that these techniques show some promise and yet at the same time we have indeed a long way to go.

Not only these exist in sonar systems, the Navy is moving to these types of sonar arrays. We hear every day of the increasing threat from the adversary and so there's a need to increase the detection rate at longer range and increase the acoustic aperature. Therefore, instead of the 15-foot sphere the ideas were to increase the acoustic aperature by mounting an acoustic array on the hull of the submarine. Essentially like the space shuttle, you cover it with tiles of some sort. Well the polyvinyl fluoride material is a piezoelectric composite polymer and that is becoming available in large sheets. It's a very sensitive material and presumably if you protect it against water somehow, you can use it as a tile to cover the whole submarine and you can get a lot of sensitive sonar systems. We have made an array with this type material. This is a copper coated, as the electrode, around the PVDF polymer and the PVDF is a highly fluorinated material and it's like a Teflon, it doesn't wet anything. So in this case you have a copper, as an electrode, for the PVDF sensor in which you use a lot of adhesives and you have some steel plating for stiffening purpose and in addition to that then, you encapsulate the whole thing with polyurethane. So you can imagine the kind of interfaces there are and the kind of special adhesive you have and once you made a structure like this and you want to then bond it to the metal hull. So there's a lot of requirement for more understanding of these adhesive interfaces. So all I'm trying to say this morning is that we need a lot of help. So I'm going to stop right here and if there are any questions, I'll be glad to answer them. Thank you very much.

Bruce Thompson and Don Thompson
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PAST EXPERIENCES IN THE DEVELOPMENT OF TESTS FOR ADHESIVE BOND STRENGTH

As many of you are probably aware, there was a rather extensive effort in adhesive bonding which was supported by the Air Force and DARPA in the mid to late 70's and I thought it would be worthwhile just going through what was done there, what was learned and so forth. And I found this a very illuminating study to do in preparing this talk and there are two things that were illuminating. The first thing of course was what we learned about adhesive bonding; the second thing that was illuminating were the jokes that are in some of the proceedings of those early conferences. I'll spare you from those, but there's some really good ones in there--kind of amazing. So what I'll focus my discussions on is a series of workshops that were held in which adhesive bonding played a key role.

The beginning of the story was a workshop that was held at the Rockwell Science Center in 1972. It was sort of a planning workshop sponsored jointly by NSF, Air Force Materials Lab, and the North American Rockwell Science Center. I'm going to talk about a number of these meetings and try to trace the historical evolution and what I'll do is show you the Table of Contents and with arrows I'll indicate the talks that particularly had to do with adhesive bonding. This first workshop was a planning activity and Forrest Williams was the Chair of a panel, Panel Three, which talked about characterization of interfaces. The purpose of this meeting was to answer the question, "What science needs to be done to enable us to develop new improved NDE techniques for adhesive bonding." For all sorts of other bonding processes and there were deliberations about, as you see, many different kinds of joining--welding, brazing, explosive bonding, so forth--this was just an attempt to characterize was diffusion involved in the bonding process, were Van der Waals forces important and so forth. I don't want you to spend time looking at all that but that just gives you a feeling of the spirit of the discussions.

What I would like you to look at is the conclusions of this panel which recommended future work that is necessary and what I find fascinating is that a

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Past Experiences in the Development of Test for Adhesive Bond Strength

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Iowa State University
Ames, Iowa 50011

In the mid-1970's, the DARPA-AFML Interdisciplinary Program for Quantitative Nondestructive Evaluation sponsored an extended research program with the goal of developing nondestructive evaluation techniques for the measurement of adhesive bond strength. Since the reports of much of that work are published in documents that are not readily available, a review of that work will be presented. Included will be the philosophy of the research plan, specific technical results achieved, and conclusions. Also mentioned will be spin-offs of some of the ideas developed to the related problem of NDE of solid state bonds.

INTERDISCIPLINARY WORKSHOP ON NONDESTRUCTIVE TESTING– MATERIALS CHARACTERIZATION

SPONSORED JOINTLY BY:

NATIONAL SCIENCE FOUNDATION
AIR FORCE MATERIALS LABORATORY
NORTH AMERICAN ROCKWELL SCIENCE CENTER

HELD AT:

NORTH AMERICAN ROCKWELL
SCIENCE CENTER
THOUSAND OAKS, CALIFORNIA
NOVEMBER 13-17, 1972

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INCLUDED:

Table I.

LIST OF JOINING PROCESSES AND SOME OF THEIR CHARACTERISTICS

Process	Diffusional Process	Metallic Non-Diffusional	Van Der Waal Forces	Homo-geneous	Hetero-geneous
Diffusion Bonding	X			X	X
→ Adhesive Bonding			X		X
Roll Bonding					
(a) Cold		X		X	X
(b) Hot	X			X	X
Electrodeposition		X		X	X
Welding	X			X	X
Brazing	X				X
Explosive Bonding		X		X	X
Polymerization			X		X
Vacuum Deposition-- Ion Plating	X (Hot Substrate)	X		X	X
Conversion Coatings		X			X
Ceramic Sintering	X			X	X
Powder Metallurgy	X			X	X

IV. FUTURE WORK THAT IS NECESSARY

There are a number of topics that need to be developed in order to make possible effective NDT and materials characterization of joined parts. They include:

1) Fundamental research on materials compatibility, atomistic details of bonding mechanisms and processes, fracture modes in interfacial regions, effects of environment upon failure modes, and identification of the important material parameters which can be used in an NDT sense for bond property determination.

2) Theoretical analysis on wave propagation aimed at determining the energy partition associated with the interaction of the wave and the interface or multiple interfaces.

3) Theoretical analysis on nonlinear effects associated with wave propagation aimed at evaluating the physical nature of the interface.

4) Expanded effort in applying modern signal processing techniques to maximize the information obtainable from any NDT experiments. These include:

   a. Autocorrelation techniques
   b. Pattern recognition
   c. Discrimination between real defects and artifacts
   d. Computerized techniques to minimize operator judgment.

5) Continued effort in the experimental fields of:

   a. Acoustic holography
   b. Transducer development and application
   c. Surface wave sampling of interfaces.

6) Development and application of new techniques to NDT of interfaces, such as X-ray-laser to image strain fields in metals.

This essentially covers the work of our panel. I want to thank the panel members for their participation and I would be pleased to have any of them answer questions that may have arisen as a result of this presentation.

lot of the ideas I've heard discussed--unfortunately I wasn't here yesterday but from the abstracts and also from other meetings--those ideas seem to have been identified to a significant extent in this panel. Of course fundamental research was called for in bonding mechanism, atomistic details of bonding, atomistic details of fracture modes, effects of environment. Wave propagation studies were called for and nonlinear effects. It was felt that nonlinear effects might give some significant insight into bonding mechanisms. In order to pull this out, modern signal processing was needed. New experimental techniques were required. I don't think these words would be too much different if we conducted that panel today. Well that was part of a larger discussion of what science was needed in NDE and it led to, after about a year and a half, of formation of a program that was managed by Rockwell International and jointly sponsored by the Air Force in what was then called ARPA now known as DARPA. And so about, as I say, about a year and a half later we had a kickoff meeting of that DARPA Air Force program and adhesive bonding played an important role in one of the sessions. I believe the meeting was fairly small, at that time there were three sessions and the second session had to do with the strength of bonded materials and dealt with both composites and adhesives. Topics had to do with the microscopic descriptions of bond strength, ultrasonic procedures for predicting bond strength, application of resonant spectroscopy to measuring the strength of bonded materials and NDE prediction of adhesive bond failure areas. What I'll do is briefly review what happened in these talks and then go through that in the succeeding years.

This was again a kickoff meeting, this wasn't work supported by this Air Force DARPA program, but this was just the state-of-the-art at its inception. And Larry Devries talked about electron paramagnetic resonance, basically a technique for detecting unbonded electrons associated with broken covalent bonds. Tennison Smith from Rockwell talked about surface characterization--ellipsometry, surface potential measurements--different techniques to characterize the state of a surface prior to bonding.

As was mentioned, I believe in Dr. Wentworth's talk, a surface condition is a very important condition, in determining whether adhesion occurs or not. There had been quite a bit of interesting work which had been done at Drexel and Paul Meyer showed some ultrasonic results which had been obtained on step lap joints.

AFML-TR-74-238

PROCEEDINGS OF THE INTERDISCIPLINARY WORKSHOP FOR QUANTITATIVE FLAW DEFINITION

HELD AT:

SCIENCE CENTER, ROCKWELL INTERNATIONAL
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JUNE 17—20, 1974

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AIR FORCE SYSTEMS COMMAND
WRIGHT—PATTERSON AIR FORCE BASE, OHIO 45433

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DEVRIES: ELECTRON PARAMAGNETIC RESONANCE

- DETECTS UNPAIRED ELECTRONS ASSOCIATED WITH BROKEN COVALENT BONDS

SMITH: CHARACTERIZATION OF METAL SURFACES (ELLIPSOMETRY, PHOTO-EMISSION, SURFACE POT. DIFF.)

- DETECT CONTAMINATION PRIOR TO BONDING

MEYER:

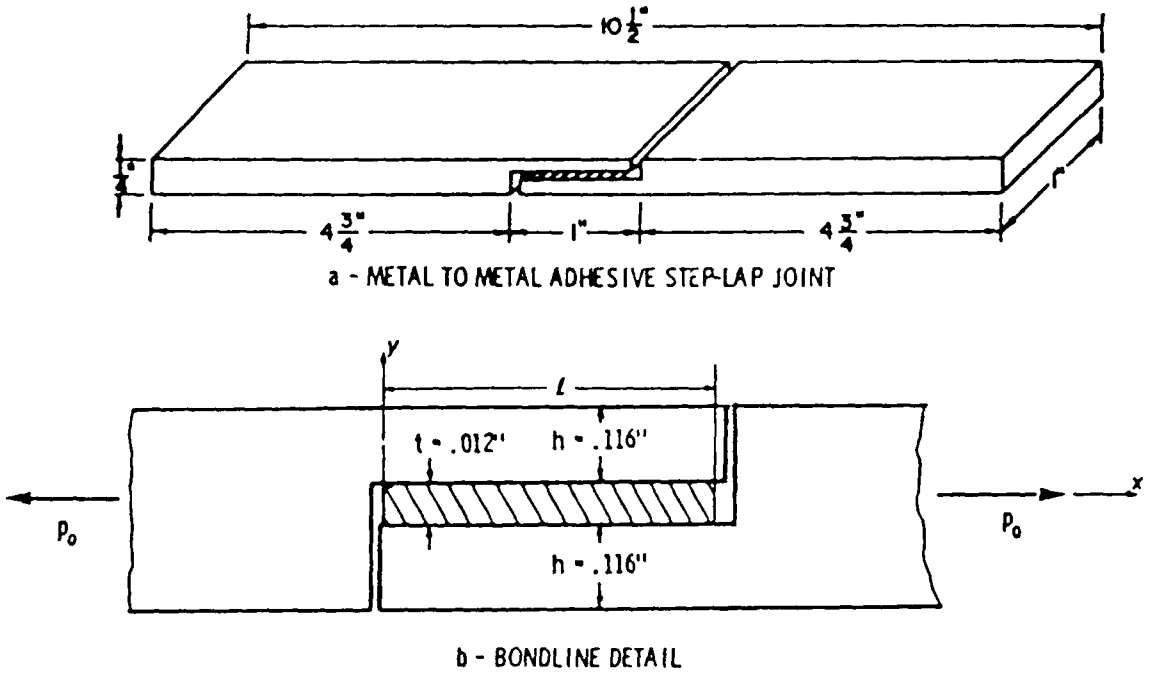


Fig. 1–Step-lap joint test specimen. (SI conversion: 1 in. = 25.4 mm)

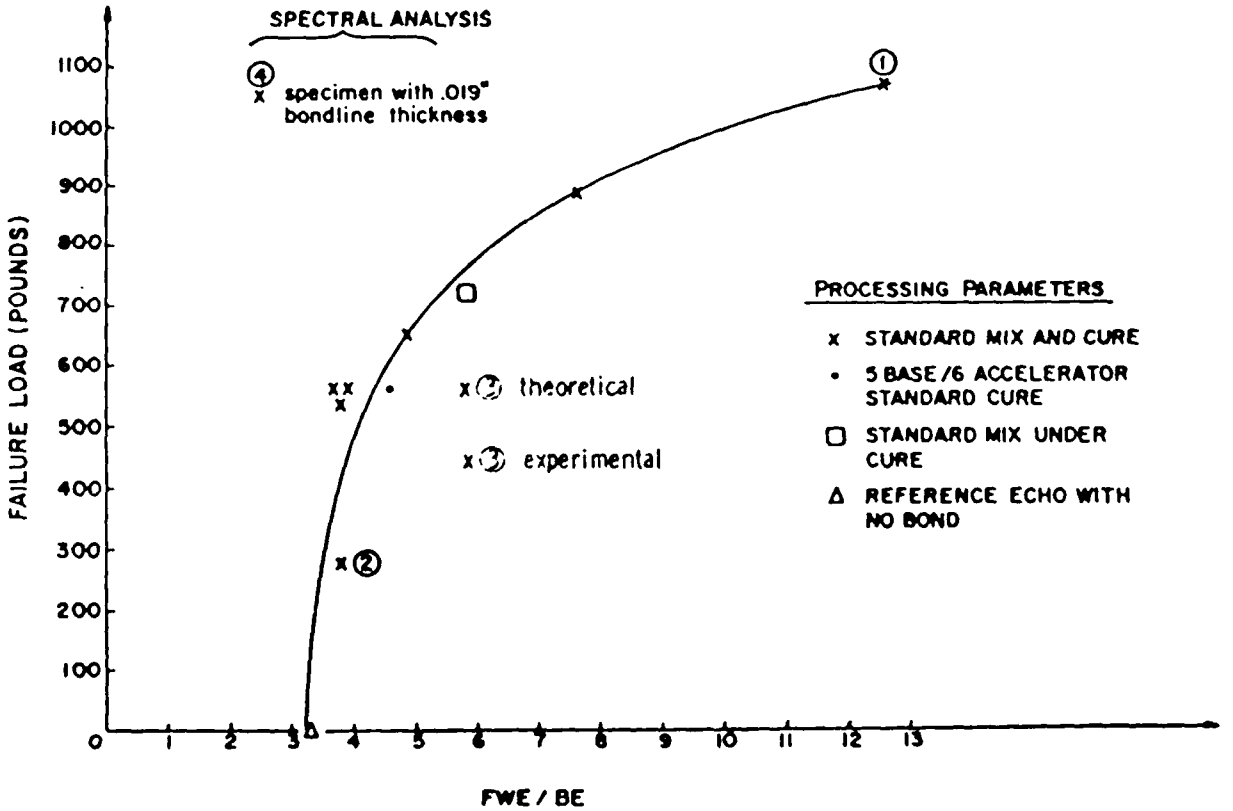
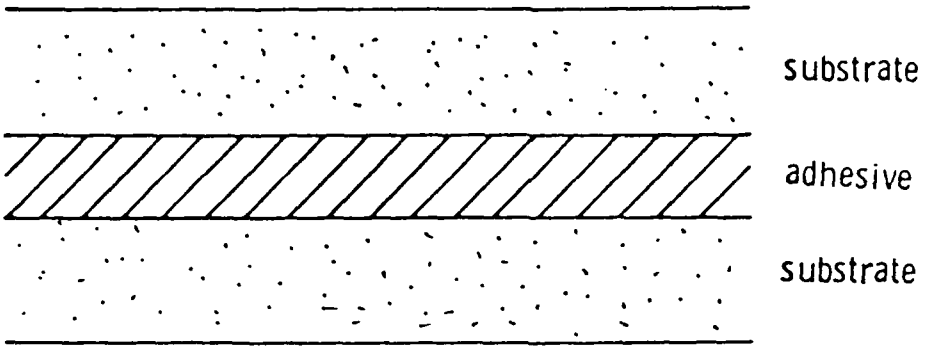


Fig. 3–Curve showing failure load versus FWE/BE for an aluminum-to-aluminum step-lap joint with 0.012 in. Scotch-Weld bondline thickness. (1 in. = 25.4 mm)

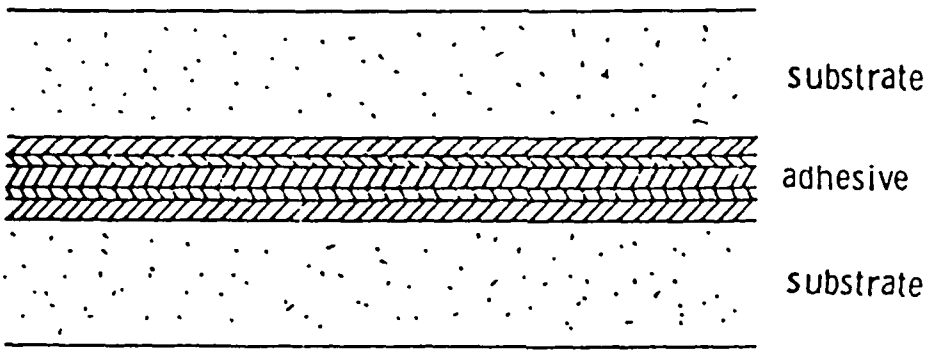
This is a fairly empirical study at that time and he had measured the ratio of the front wall echo to the back wall echo and simply plotted that versus failure load and had observed a correlation. There wasn't too much science to this at the time but a correlation had been observed which was viewed as promising and suggested that ultrasonics might be a good way to try to measure bond strength. And he'd even proposed some physical models because it was clear you had to do some theoretical analysis to try to interpret those results and he postulated that a good bond might look as this upper sketch, we might consider a three-layer model to represent a good bond in which you had a substrate adhesive to substrate. He postulated that some migration effects during bonding might actually lead to density gradients and these might have a role in bond strength deterioration so you might want to ask the question, how does an ultrasonic wave interact with this structure. And finally he suggested that under a number of conditions you might have uniformly distributed microscopic disbonds between the adhesive and the substrate and it would be of value to understand how this structure is bonded. In some sense we might associate this with some cohesive weakness and this with some adhesive weakness although I'll say a little more about that later on.

Well, prevalent in the practical community at the time was this idea of cohesive and adhesive bond strength. In this slide I sort of illustrate a microscopic and a macroscopic interpretation of that. The macroscopic view, at least as I personally encountered it, was represented by the test that would be done at our operating divisions at North American Rockwell and basically when they did a failure test they would look and they would see that the fracture surface is shiny, in other words did it break at the interface between the adhesive and the metal. Or if there were some adhesive stuck to both sides of the fracture surface, it did break within the adhesive, in which case that was a cohesive failure. I believe in a lot of operational programs one would sometimes talk about failure as 40% cohesive or 60% adhesive and so forth. So this led to the idea that we ought to learn how to measure these two kinds of strength, cohesive and adhesive strength. Of course in a more microscopic view, you're really talking about some fracture process that may during part of its path be in this interphase region we heard about this morning and other paths that go through the bulk adhesive. So this idea of cohesive and adhesive strength--can we measure those two parameters assuming they're meaningful parameters--played a

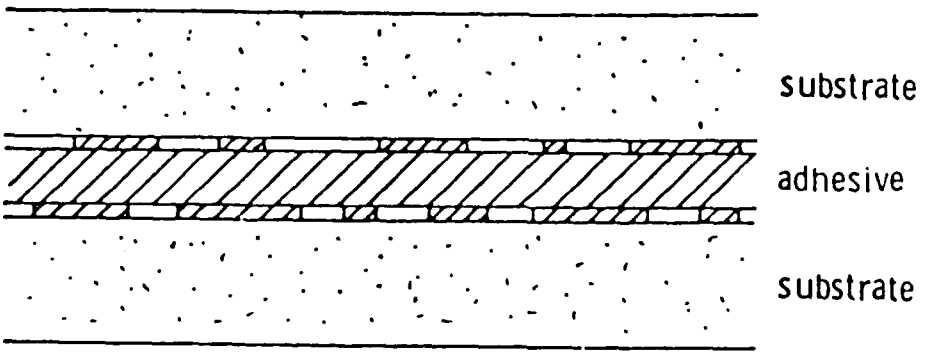
PROPOSED PHYSICAL MODELS:



a.) three layer model — PERFECT BOND



b.) N-Layer model — DENSITY GRADIENTS ASSOCIATED WITH MIGRATION OF CONSTITUENTS DURING BONDING

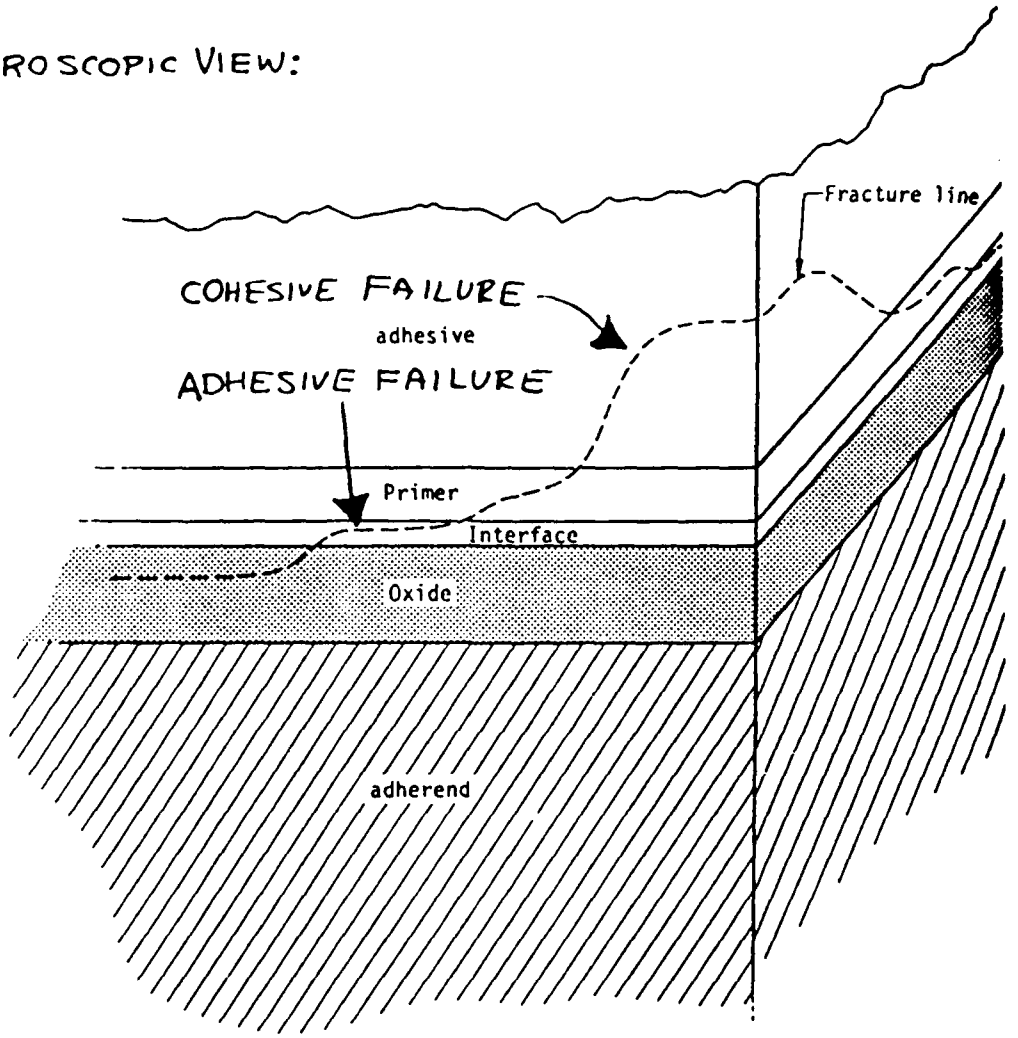


c.) double area discontinuity model — UNIFORMLY DISTRIBUTED MICROSCOPIC DISBONDS RESULTING FROM SURFACE CONTAMINATION

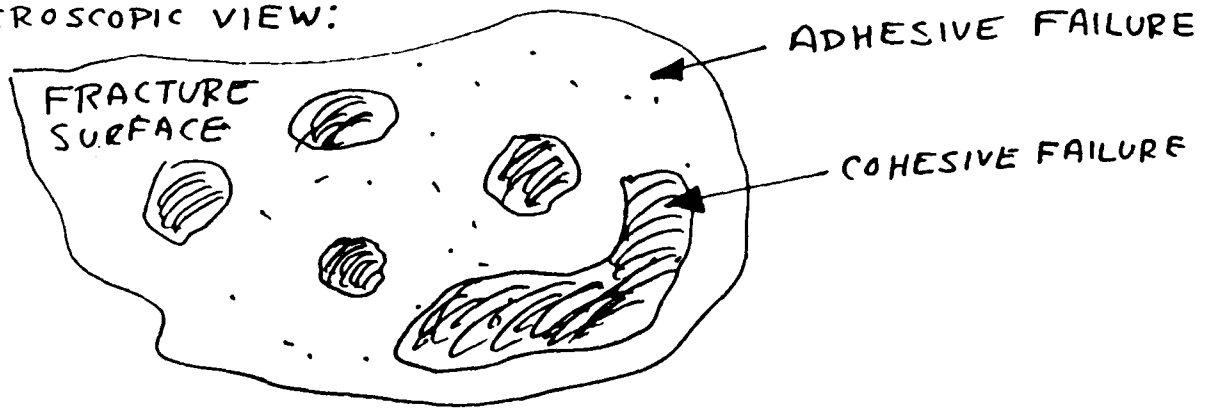
FIG. 4 - MODELS USED IN ADHESIVE BOND ANALYSIS

"COHESIVE" VERSUS "ADHESIVE STRENGTH"

MICROSCOPIC VIEW:



MACROSCOPIC VIEW:



key role in defining a program which adopted the following premise--that was that there were many laboratory techniques and people working on new techniques to detect voids, porosity, and other kinds of discontinuity--so we would focus on these more subtle effects, the question of determining weak adhesion at adhesive metal interfaces, and poor cohesive strength for cohesion within the bulk of the bond material itself. In the area of adhesion there were really two parts. There was the part having to do with could you develop a nondestructive technique, but also it was felt perhaps you'd have to study the surfaces themselves so you could better understand the material science of what constituted and what produced good adhesion. Similar ideas but in a more elementary form than we heard talked about by Dr. Wentworth.

After a year, what had happened? In 1975 there was another workshop in July. During that workshop there's now a lot of talks about adhesives and adhesive bonding. There was a program with several investigators sponsored by the Air Force in ARPA and there were additional talks of people representing the practical community and R&D programs supported by other sources. Some of these I'll just touch on very briefly. Dave Tupper from the Air Force talked about the damage tolerant philosophy. The whole point of course was just as in airframes. We used to design airframes according to safe life, concepts, measure the fatigue life, divide by four and so forth, but now we had to recognize the existence of flaws and postulate an initial flaw size. Shelton discussed aspects of the PABS program, the Primary Adhesive Bonded Structure technology which was involved in evaluating the state-of-the-art NDE technology.

Tennison Smith presented some more recent results about using surface characterization techniques, ellipsometry, Auger Analysis and so forth, to characterize the state of surfaces and to try to develop relationships between the physical and chemical properties of the interfaces and the resulting bond strength. Jim Seydel talked about some other work, some ultrasonic correlations which were fairly preliminary results and not too much different from the other things I'm going to present, so I won't elaborate on that work any further.

In the area of the ultrasonics, the research was devoted to possibly fieldable techniques. There were two major programs--one of which had George Alers as the principal investigator and he was really studying the adhesion

ARPA / AFML PROGRAM PLAN

PROJECT II – NONDESTRUCTIVE MEASUREMENT OF STRENGTH RELATED PROPERTIES

A. ADHESIVE BOND STRENGTH

PREMISE: MANY LABORATORY TECHNIQUES AVAILABLE TO DETECT VOIDS, POROSITY & OTHER DISCONTINUITIES

GOAL: SEEK TECHNIQUES TO MEASURE THE MORE SUBTLE PROBLEMS OF DECTING

- WEAK "ADHESION" AT ADHESIVE/METAL INTERFACE
- POOR "COHESIVE STRENGTH" WITHIN BOND

AFML-TR-75-212

PROCEEDINGS OF THE ARPA/AFML REVIEW OF QUANTITATIVE NDE

HELD AT:

SCIENCE CENTER, ROCKWELL INTERNATIONAL
1049 CAMINO DOS RIOS
THOUSAND OAKS, CALIFORNIA 91360

JULY 15-17, 1975

JANUARY 1976

TECHNICAL REPORT AFML-TR-75-212
FIRST ANNUAL REPORT FOR PERIOD 3 JUNE 1974 – 17 JULY 1975

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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INCLUDED:

TUPPER: DAMAGE TOLERANCE PHILOSOPY AS APPLIED TO NEW AIR FORCE SYSTEMS

- FATIGUE TEST/SAFE LIFE CONCEPT NOT ADEQUATE
- MUST ASSOME INTIAL FLAW SIZE

SHELTON: PRIMARY ADHESIVE BONDED STRUCTURE TECHNOLOGY PROGRAM (PABST)

- EVALUATE STATE-OF-ART CAPABILITY TO DETECT AND DISCRIMINATE BETWEEN CRITICAL AND NON-CRITICAL DEFECTS

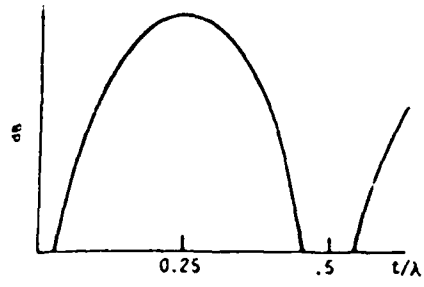
SMITH: USE OF SURFACE CHARACTERIZATION TECHNIQUES TO RELATE PHYSICAL AND CHEMICAL PROPERTIES OF INTERFACES TO RESULTANT BOND STRENGTH

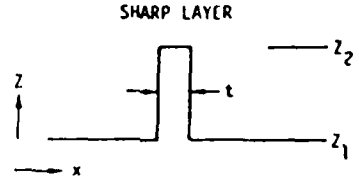
SEYDEL: OBSERVED SUBTLE DIFFERENCES ON A SERIES OF SPECIMEN. INITIATING DESTRUCTIVE TESTS TO SEEK CORRELATIONS.

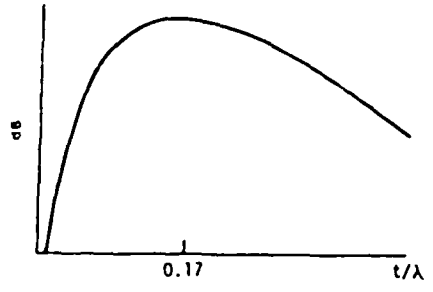
problem. The question was what do you have to measure to determine adhesion. And in that study he developed three models for an interface. You might acoustically imagine an interface to be a very sharp layer and this is similar to one of the models that Meyer had put forth. But we might imagine it had some finite width to it. But one of the problems with either of these models is this width is very, very small; really, physically you might imagine it's on the order of angstroms or hundreds of angstroms so maybe we should just consider this interface as a single plane and we might try to model this mathematically by some changes in the boundary conditions relating the continuity of stress and displacement across that interface and in fact, it led to the so-called spring model that I'll say something about later on. Using these three models, George predicted what the frequency dependence of the ultrasonic reflections from those interfaces should be.

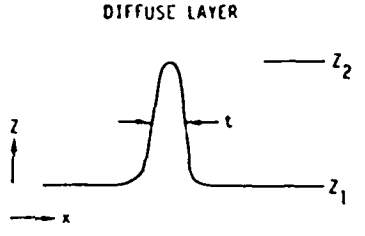
We all know that a sharp layer will produce the frequency dependence indicated at the top of the slide, a series of peaks and nulls in the backscattering. If you have a diffuse layer that's all sort of smeared out and if you have the spring model, the reflectivity just increases with frequency but you don't have any of the subsequent structure. So George set out to say can we measure these phenomena and try to relate those to the adhesive strength of an interface. He looked at two kinds of specimens. First, he took some Lucite and he chemically bonded them, he put a solvent, pushed them together and he created this diffuse layer and what he observed very nicely was that the reflection coefficient as a function of frequency had this characteristic peak structure and furthermore these three solid lines correspond to three strengths in case you can't read them, this is 364 kilograms per centimeter squared, 383 and 409 so the stronger strengths very clearly produced the lowest reflectivity and that was a very positive encouraging result. But real bonds may not have this extended spatial region that he achieved with his chemical bonding so then he did some thermal bonding--basically diffusion bonded. He bonded specimens together under temperature and that didn't work very well at all. He found that the reflectivity was basically independent with some scatter bands of frequency and strength and he didn't see much of an encouraging relationship. So he concluded that we really needed to understand this interaction of waves with an interface better and perhaps some other wave modes would be required which would have a stronger interaction with the interface and maybe the energy should even

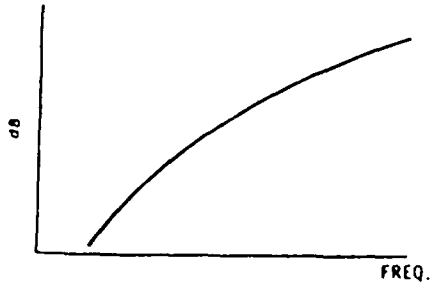
ALERS:

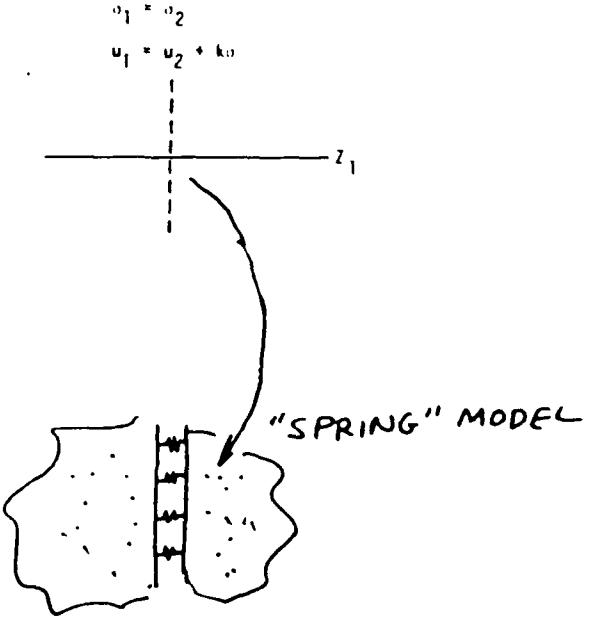

dB
0.25
.5
t/λ


SHARP LAYER
Z_2
Z
t
Z_1
x

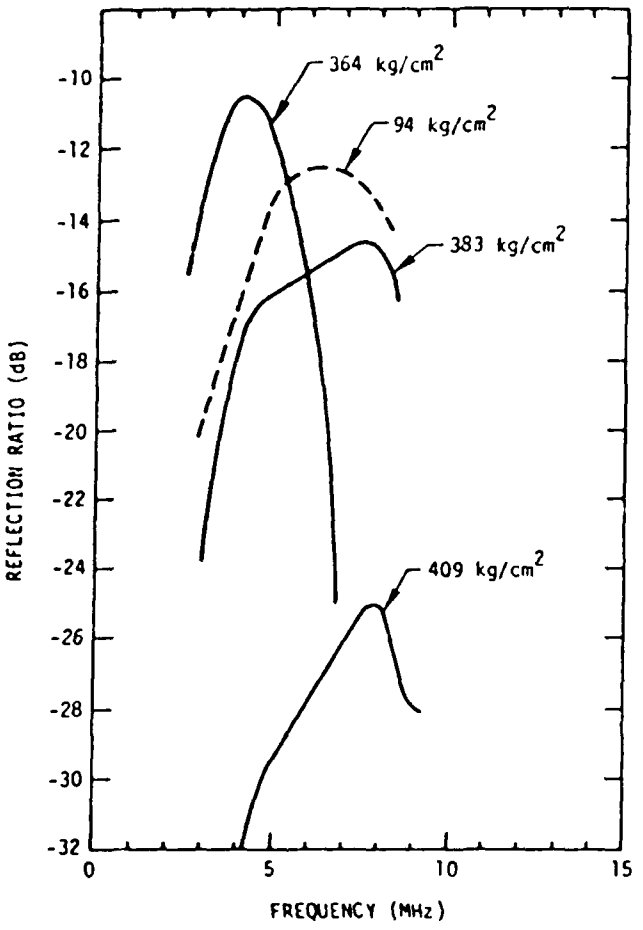

dB
0.17
t/λ


DIFFUSE LAYER
Z_2
Z
t
Z_1
x


dB
FREQ.


$\omega_1 = \omega_2$
$u_1 = u_2 + k\omega$
Z_1
"SPRING" MODEL

"CHEMICAL" BONDS:



"THERMAL" BONDS:

REFLECTIVITY INDEPENDENT OF FREQUENCY AND STRENGTH

CONCLUSION:

- NEED IMPROVED MODELS FOR WAVE INTERACTIONS WITH INTERFACES
- USE OTHER WAVE MODES

propagate along the interface so it in some way sampled the interface continuously rather than going through the interface in which you just pass by--basically you see the interface in one pass only.

At the same time there was some very interesting work going on at Drexel and Joe Rose was the principal investigator of that. He was really concerned with now the bulk properties of the adhesive, not the interface and he developed some computer models to answer the question, if the attenuation of adhesive changes, can we see that from reflectivity measurements and of course these graphs indicate that you can, here's the reflectivity as a function of frequency and you see how that is changed and particularly the structure of this null is changed as you change the attenuation of the adhesive. Now of course, underlying this was the idea that the cohesive strength of the polymeric material is strongly related to both the velocity of ultrasound in that material and the attenuation having to do with relaxation processes associated with unbonded side change. So there's some physics behind all that that I won't talk about but that was the reason for those studies.

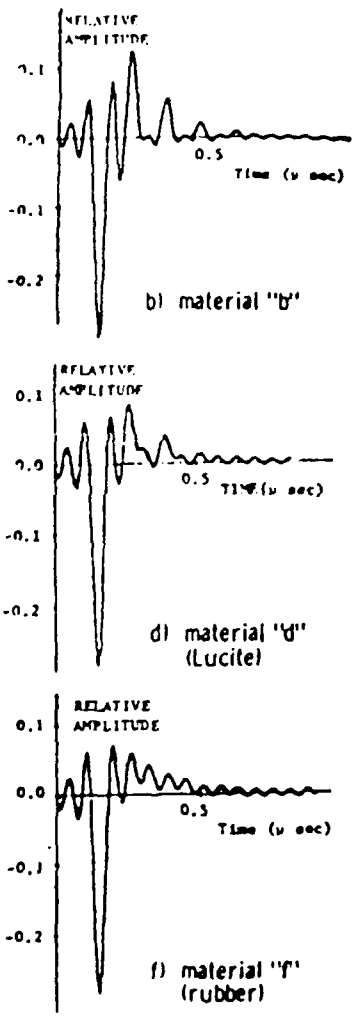
Well, we go on another year. In 1976 we all met at Asilomar. This is the end of two years of research on this problem. Again, a series of papers, you don't need to read all of those--I'm going to mention them individually. Bascom talked about microvoids--there was a lot of discussion of the mechanisms of microvoid formation and he showed the types of microvoids you would expect that would be developed during adhesive bonding were very close to what you might consider as the fracture critical defects, so we really had to think about defects as well as bulk properties. Wolfram talked about inelastic electron toning spectroscopy, a sophisticated way again of characterizing the chemical state of the interface, Mike Buckley from the Materials Lab talked about their efforts in developing improved ultrasonic instrumentation to measure some of the phenomena that Rose had talked about.

Let me turn back to Alers. The first year Alers tried to send ultrasound through the bond, had found you could say a lot about extended bonds produced related to fusion but not too much about interface bonds. So as I said at that time, the next step was well, what happens if we try to propagate a wave parallel to the interface. So we did some study on these lap shear specimens and the

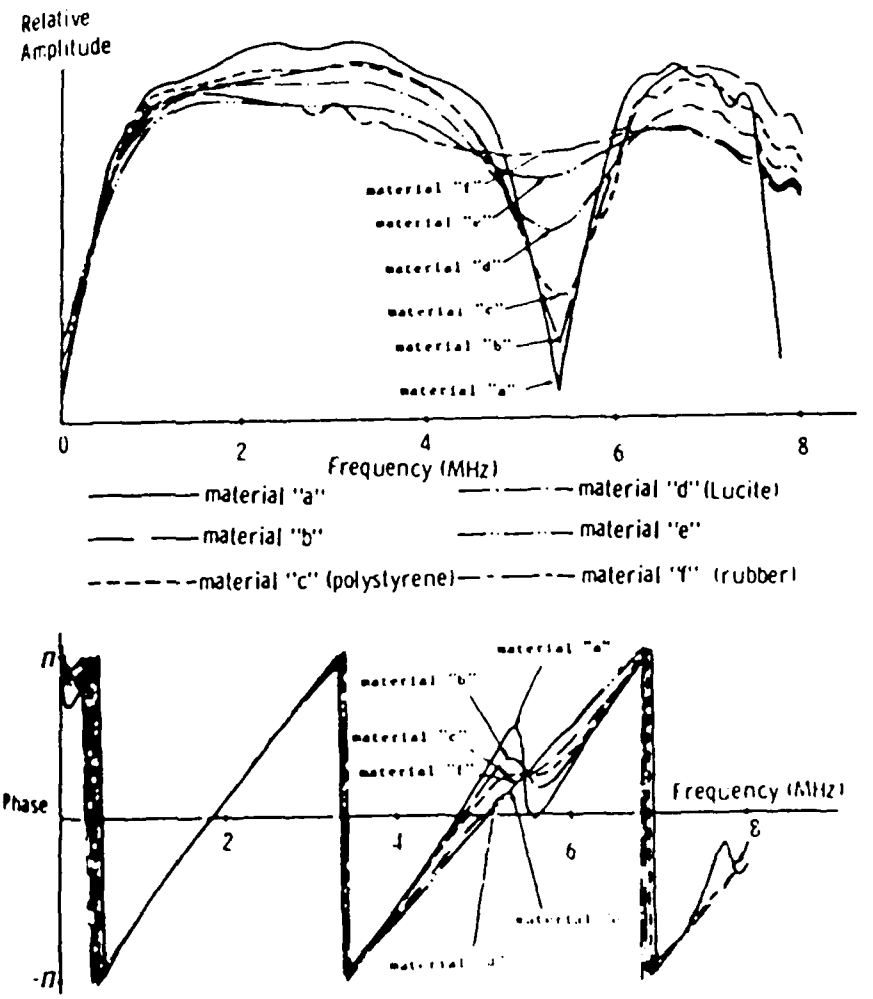
ROSE:

EFFECTS OF DIFFERENT ATTENUATION FUNCTIONS

TIME DOMAIN



FREQUENCY DOMAIN



AFML-TR-77-44

PROCEEDINGS OF THE ARPA/AFML REVIEW OF PROGRESS IN QUANTITATIVE NDE

SCIENCE CENTER, ROCKWELL INTERNATIONAL
1049 CAMINO DOS RIOS
THOUSAND OAKS, CALIFORNIA 91360

HELD AT:

ASILOMAR CONFERENCE GROUNDS
PACIFIC GROVE, CALIFORNIA
AUGUST 31 - SEPTEMBER 3, 1976

SEPTEMBER 1977

TECHNICAL REPORT AFML-TR-77-44
Second Annual Report 18 July 1975 – 3 September 1976

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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INCLUDED:

BASCOM: MICROVOIDS CREATED BY AIR ENTRAPMENT AND EFFECT ON MECHANICAL PROPERTIES

- AIR INITIALLY CAUGHT AT GLASS/ADHEREND INTERFACE
- SUBSEQUENTLY DISPLACED INTO ADHESIVE
- $r_c \sim 70\text{-}140\mu m$

WOLFRAM: PROBLEM:

- CONVENTIONAL METHODS NOT SENSITIVE TO RESPONSE OF INFINITESIMAL THICKNESSES
- NEED TO SENSE CHEMICAL AS WELL AS MECHANICAL STATE

USE INELASTIC ELECTRON TUNNELING SPECTROSCOPY (IETS) TO STUDY IN-SITU CHEMICAL STATE OF METAL OXIDE / ADHESIVE INTERFACE

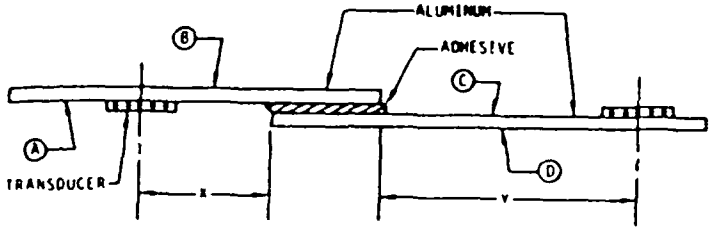
BUCKLEY: EXPERIMENTAL ULTRASONIC TECHNIQUES

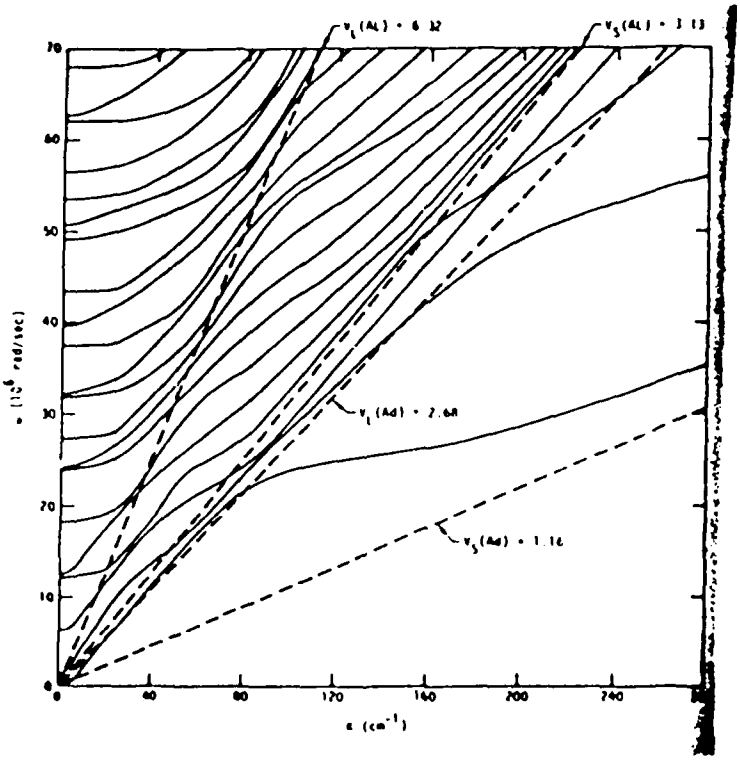
- DIGITAL DATA ACQUISITION
- PLANE WAVE THEORY
- INVERT FOR α, v
- HOPE FOR EMPIRICAL CORRELATION WITH BOND STRENGTH

basic idea was let's put a transducer here, let's try to get energy to propagate through the interface, pick it up over here and measure something about the guided waves of this three layer structure and see how that's influenced by the bond. Some theory was done calculating how Lamb waves of the simple plate are modified in this three layer structure and some sensitivity analyses were done as to how this dispersion curve would be modified by the boundary conditions at the interface. There was a very interesting prediction made and this is illustrated by this graph of phase velocity versus frequency and what happened is at low frequencies, this structure would vibrate and flexure just like a single plate. As you increase frequency that vibration mode would become a Rayleigh wave propagating on the face but a higher frequency of this mode would suddenly plummet down in phase velocity and end up as a shear wave propagating inside the adhesive layer itself. If you did a sensitivity study of the change and the phase velocity of that wave as a function of some modulus associated with a thin interfacial layer, you found that the velocity was very, very sensitive to that interfacial layer. So this said here's a way we might be able to really concentrate our sensitivity to the interface itself. It turned out that was very difficult to measure and the reason it was difficult to measure was the very region that the theory said was sensitive was the region which all the energy was in the adhesive and you couldn't couple into it through the face sheet--very simple problem. But there were some other modes that had less sensitivity but still looked interesting and one of these was a very low frequency resonance vibration through the thickness--the so-called dumbbell mode--in which the face sheets were moving in opposition and the glue was just acting like a spring and if you calculated the stresses were very high at these interfaces and George had a set of specimens prepared, some by adhesive, all had the same nominal cohesive strength but surface preparation significantly changed the failure loads which were adhesive in nature and he found, not a large, but a systematic and consistent difference in the resonant frequencies of this low frequency mode. So he couldn't do what seemed to be the most elegant experiment from the theory but he did a related one which showed some positive results.

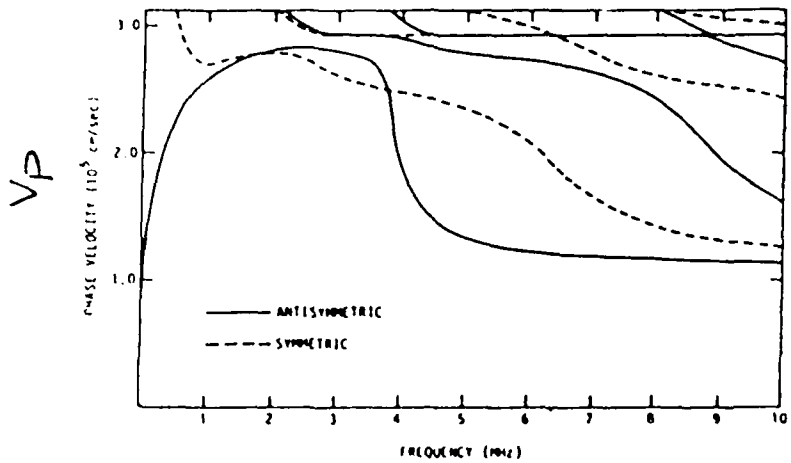
At the same time the people at General Dynamics, Paul Flynn working with Francis Chang and others, carried on with this idea of the bulk property of the adhesive--they did some work on Chemlok 304 adhesive and they found out there's some very good correlations between the strength of the bond in both the

ALERS:


ALUMINUM
ADHESIVE
B
C
A
D
TRANSDUCER
X
Y


V_l (Al) = 6.32
V_s (Al) = 3.13
V_l (Ad) = 2.68
V_s (Ad) = 1.16
ω
α (cm⁻¹)
0
40
80
120
160
200
240
10
20
30
40
50
60
70

K



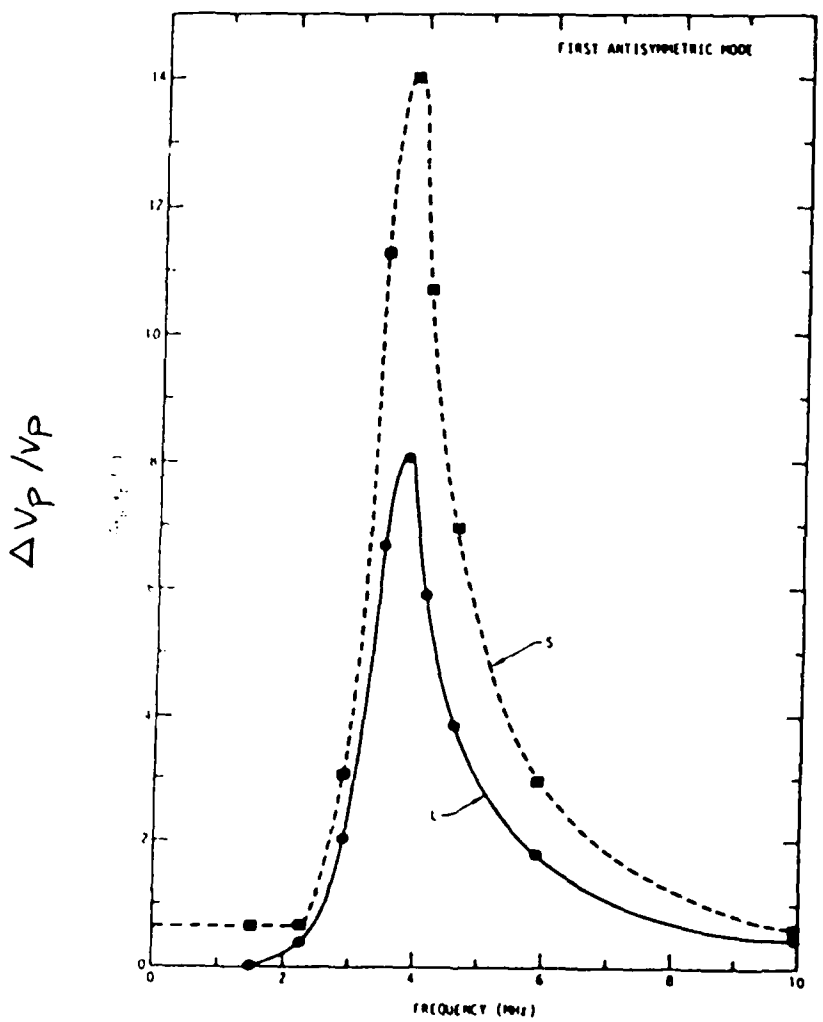
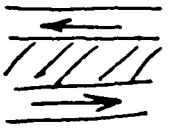


Figure 4. Percentage change in propagation velocity of the first antisymmetric trapped mode produced by insertion of a very thin layer of material at the interface having a small shear stiffness (curve S) or a small compressional stiffness (curve L).

FUNDAMENTAL THICKNESS VIBRATION



"DUMBELL MODE"

σ_F (psi)	f_R (kHz)
1550	467
1783	467
1790	458
1843	451
2440	469
2460	474
2476	472
2533	474

FLYNN:

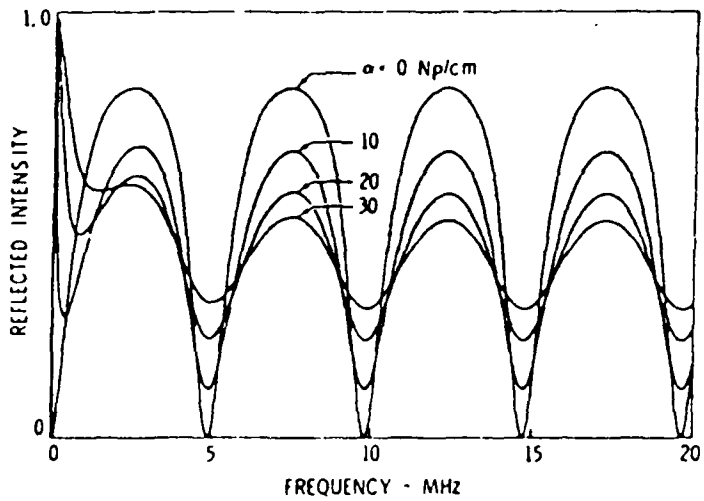
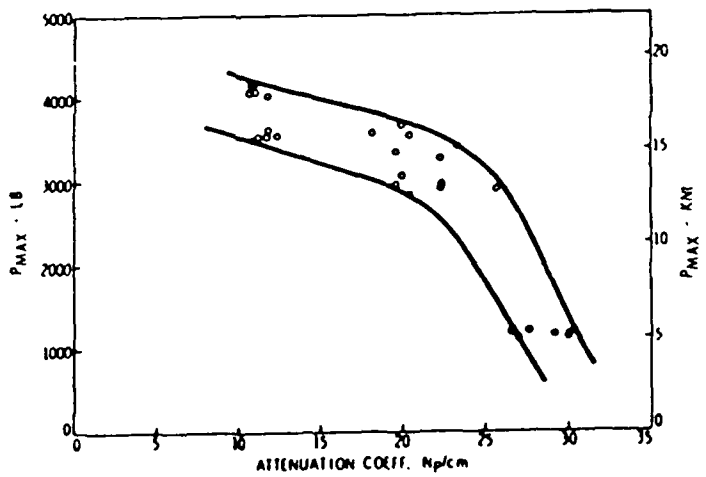
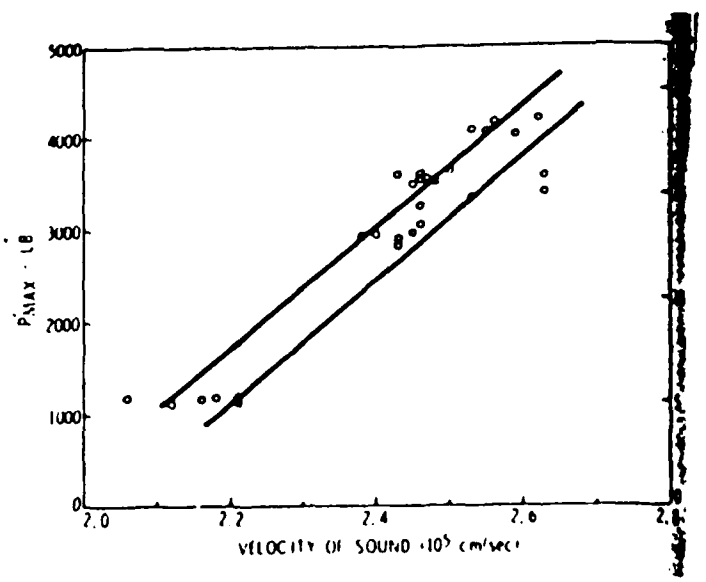


Figure 2. Theoretical Spectra for a 0.0254 on Adhesive Layer Between Aluminum Adherends

CHEMLOK
309
ADHESIVE





attenuation coefficient and the velocity. So at the end of two years of this program, we had then come to the point of the following conclusions. That the material properties of the adhesive, that is the bulk adhesive, can be deduced from ultrasonic measurements and from these correlation strength--whatever we mean by that--correlations can be obtained and that adhesive strength measurements are more difficult because of the smallness of the interfacial interaction region but the two candidate techniques were identified for further study.

Well we went on to 1977, there was another meeting at Cornell, not quite so many papers. At this time, as in all fields, interest tends to move in other directions after a period of time. There was a very nice discussion by Devries of fracture mechanics of joints, and the group at the University of Missouri carried on further their inelastic electron tunneling work and aimed at the chemical characterization of the bond. The second year studies were done on very simple adhesive systems and got some very encouraging results. In the third year studies we said let's add some scrim cloth and use a more complex adhesive system and see how these techniques we developed in the second year performed. And the answer wasn't very encouraging. This isn't just the work of Alers, I'm sorry, this was both the work of the General Dynamics Group of Paul Flynn and associates and Alers and associates at the Science Center. You can't read the axes on this, I apologize for that, you can't read them in the originals very well either. But this is a graph of shear strength versus ultrasonic velocity and shear strength versus attenuation. These are for materials cured at different temperatures, but there's a lot of scatter. When you put that scrim cloth in there, the correlations that we observed previously seem to deteriorate quite a bit both through the effect of the cohesive strength and these measures of adhesive strength. And so the conclusion that was drawn at that time was the following. The cohesive and adhesive strengths can be measured on carefully prepared joints, but when you get to more complex joining systems, two phase systems, for example adhesive with scrim cloth, you observe much greater scatter. One interpretation was that the scrim cloth probably dominates the attenuation while the adhesive controlled strength, in other words where measurement is no longer dominated by the strength related property. It is also concluded that there is a lot of scatter in the strength measurements as well and we need improved strength tests and that was interesting because one of the earlier speakers said that again so we still seem to need improved strength tests.

CONCLUSIONS AFTER TWO YEARS

- MATERIAL PROPERTIES OF ADHESIVE CAN BE DEDUCED FROM ULTRASONIC MEASUREMENTS AND, FROM THESE, "COHESIVE STRENGTH" CORRELATIONS CAN BE OBTAINED.
- "ADHESIVE STRENGTH" MEASUREMENTS MORE DIFFICULT BECAUSE OF SMALLNESS OF INTERFACIAL INTERACTION REGION. TWO CANDIDATE ULTRASONIC TECHNIQUES IDENTIFIED FOR FURTHER STUDY

AFML-TR-78-55

PROCEEDINGS OF THE ARPA/AFML REVIEW OF PROGRESS IN QUANTITATIVE NDE

SCIENCE CENTER, ROCKWELL INTERNATIONAL
1049 CAMINO DOS RIOS
THOUSAND OAKS, CALIFORNIA 91360

HELD AT

CORNELL UNIVERSITY
ITHACA, NEW YORK
JUNE 14-17, 1977

MAY 1978

TECHNICAL REPORT AFML-TR-78-55
Third Annual Report 4 September 1976 – 30 June 1977

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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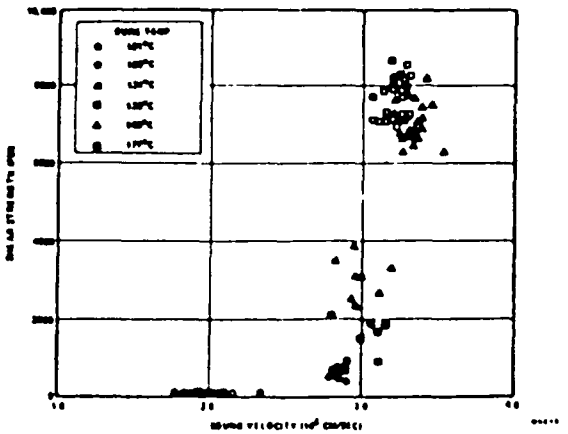
INCLUDED:

DEVRIES: FRACTURE MECHANICS OF JOINTS AND TESTS TO DETERMINE MODEL PARAMETERS

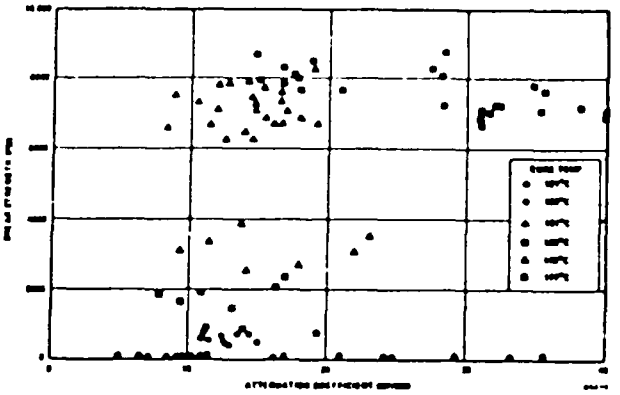
WHITE:
- JETS ONLY METHOD ALLOWING IN SITU STUDIES OF ADHESIVE/OXIDE INTERFACE BONDING
- CAN STUDY MOLECULAR CHANGES DUE TO TIME, TEMPERATURE & PERMEATING WATER
- NOT DIRECTLY APPLICABLE AS FIELD NDE TECHNIQUE

ALERS:

COHESIVE SHEAR STRENGTH (COMPRESSION

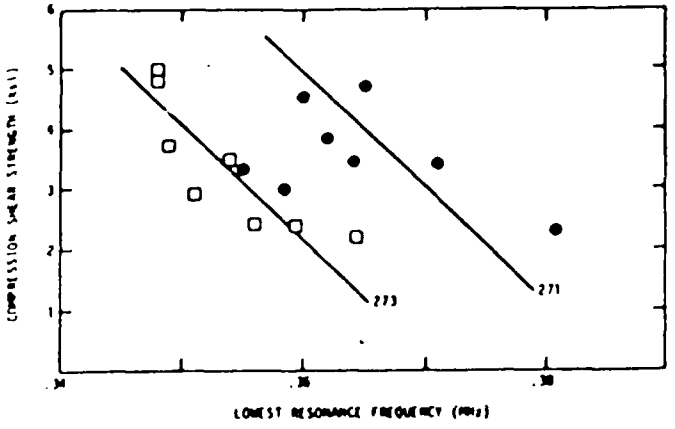


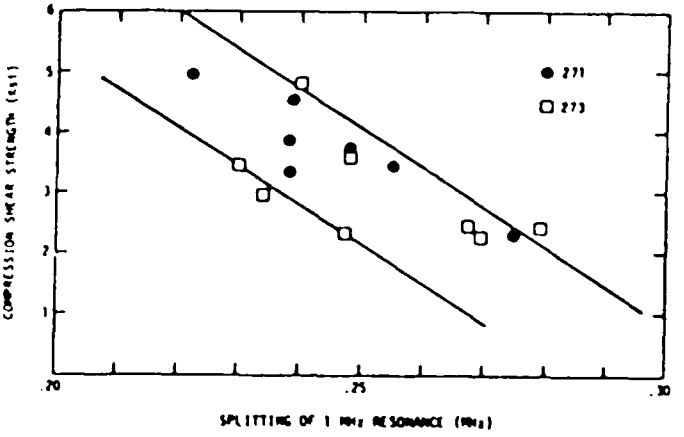
V_L



α

ADHESIVE SHEAR STRENGTH





CONCLUSIONS AFTER THREE YEARS

- COHESIVE AND ADHESIVE STRENGTHS CAN BE MEASURED ON CAREFULLY PREPARED JOINTS
- TWO PHASE SYSTEMS (ADHESIVES WITH SCRIM CLOTH) EXHIBIT EXCESSIVE SCATTER
  - SCRIM CLOTH PROBABLY DOMINATES ATTENUATION WHILE ADHESIVE CONTROLS STRENGTH
  - IMPROVED STRENGTH TESTS ALSO NEEDED

Some more work went on and was reported in 1978. I'm not going to go through the details of that. Those were poster sessions and there's not too much information in the proceedings about them and the conclusions weren't that much different than you've already heard. The General Dynamics Group did some more work and was looking at multiple parameters. The emphasis has shifted somewhat in a sense to more empirical techniques--adaptronics was involved, some work with adaptive learning systems. There were encouraging results but a lot of problems still seemed to exist.

So let me then come to the final year because I think something of fair significance occurred during this year. This was in 1979--a meeting that was held at Scripps in California and there were only two papers here. One by Segal and one by Thomas and Rose at Drexel and they reported on some work on empirical techniques, pattern recognition, and so forth and they obtained some very good results. Sort of independent of these mechanistic considerations we talked about but on a particular set of samples they obtained some very nice correlation coefficients So that was a very interesting result but the other thing I really wanted to emphasize was that there was a planning study done saying where are we really in this field.

Many of you may have already read this but this was a document, I think about 20 pages long, produced by Frank Kelley, Wolfgang Knauss, and Dave Kaelble in which they really made a detailed plan of action of where should we go in adhesive bonding. I can't do it justice in the time that I have because I think I've already exceeded it, but they talked about four basic ideas: accept/reject methodology based on fracture mechanics, flaw growth model, stress analysis, and nondestructive measurement techniques. And the real message was this whole idea of adhesive and cohesive strength isn't going to get us anywhere because failure is really dominated by defects, it's not dominated by some average physical properties of the adhesive and the interface. It's defect dominated and we better face up to that and this was really a plan and in a sense a proposal to DARPA saying, hey, if you guys really want to solve this problem, this is what you have to do and not in the report, but implicitly, this is what it's going to cost you.

So that's really where I'm going to stop the historical aspects of my talk. I'll just make one other brief illusion to some work that's going on now and if

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1049 Camino Dos Rios
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JANUARY 1979

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1400 WILSON BOULEVARD
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AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

SESSION VI - NDE FOR ADVANCED MATERIALS (POSTER) PAGE

CHANG: • FOKKER BOND TESTER INADEQUATE

• FREQUENCY DEPENDENT INFORMATION (e.g. Q) POOR CLASSIFIERS

• AMPLITUDE PARAMETERS (e.g. RESONANCE DEPTH) BETTER RESOLUTION

• MULTIPLE PARAMETER PROCEDURES REQUIRED

ALERS: • CERTAIN RESONANT FREQUENCIES & MINIMA DEPTH PROVIDE INTERFACE PROPERTIES

• MUST SOLVE AN INVERSE PROBLEM

• EXPERIMENTAL CORRELATION BETWEEN BOND STRENGTH AND FREQUENCY OF "DUMBELL MODE"

AFWAL-TR-80-4078

PROCEEDINGS OF THE DARPA/AFML REVIEW OF PROGRESS IN QUANTITATIVE NDE

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MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
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INCLUDED:

SEGAL:

COMPUTER AIDED TEST BED WITH ADVANCED PATTERN RECOGNITION TECHNIQUES

	Training Set (64)		Test Set (90)	
	Reliability	Loss Function	Reliability	Loss Function
Rose and Thomas Fisher Algorithm (adhesive defect only)	96%	100%	88%	100%
Fisher Algorithm Using Fourier Spectrum Features	97%	100%	74%	87%
Fisher Algorithm Using Transfer Function Features	91%	97%	84%	91%

Figure 5. Sample Problem Results Compared with Results of Previous Adhesive Bond Study

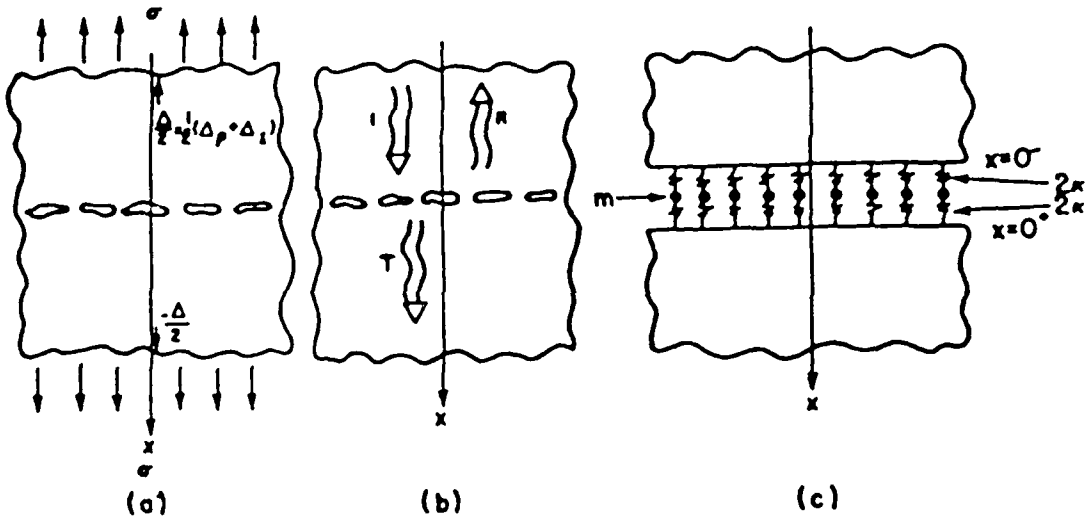
KELLEY, KNAUSS, KAELBLE

DETAILED PLAN OF FUTURE ACTION

- ACCEPT/REJECT METHODOLOGY BASED ON FRACTURE MECHANICS
- FLAW GROWTH MODELS
- STRESS ANALYSIS
- NON-DESTRUCTIVE MEASUREMENT TECHNIQUES

people would like to discuss those ideas further, we could at the discussion session. This idea of a spring model of an interface has been reborn. It started in this adhesive bond strength problem but it's been reborn in solid state bonding and we've been doing quite a bit of work on that. The basic question is how do we model the interaction of ultrasonic waves into certain materials which have some sort of microscopic array of cracks at the interface and we've developed some models in which we approximate that boundary condition by a set of springs, we have some physical bases to relate. The constants of those springs, the spring stiffness, the spring constant for unit area to parameters such as at the uncracked area divided by the total area. So the physical topology of the contact some model experiments have been done and this does seem to be a good way to think about this one aspect of the problem, that is partially contacting interfaces and this is some work done by Otto Buck of which I think it may be reported elsewhere in this meeting in which he measured the reflection coefficient in which he destructively tested the samples, he measured the topology of contact, the area fraction of contact, and the separation of the contact. He predicted the spring constant, and so then he plotted his measure reflection coefficient versus the predicted spring constant and determined from this destructive test and then on that graph he added the solid line which is the theoretical dependence of the reflection coefficient on that spring constant and it all worked very well.

So this seems to give us a way to think about one aspect of the problem and that's being presently used in four programs in solid state bonding at our laboratory. We're looking at a model system for diffusion bonding of copper that Buck was concerned with and some work on pinch welds of interest to Sandia. Both of those papers have been written on those subjects and they'll be published in a special issue of the journal of NDE which is forthcoming. Some work on diffusion bonding for the Air Force being discussed in a paper by Frank Margetan this afternoon and then some work on some fatigue cracks.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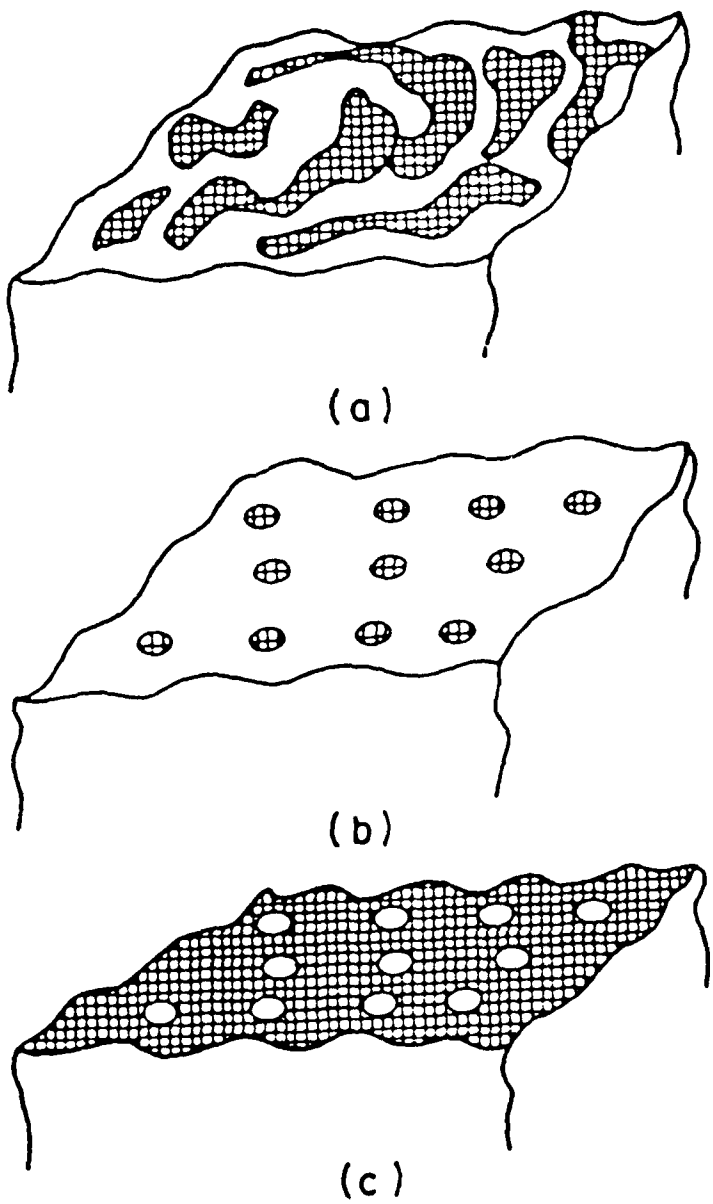
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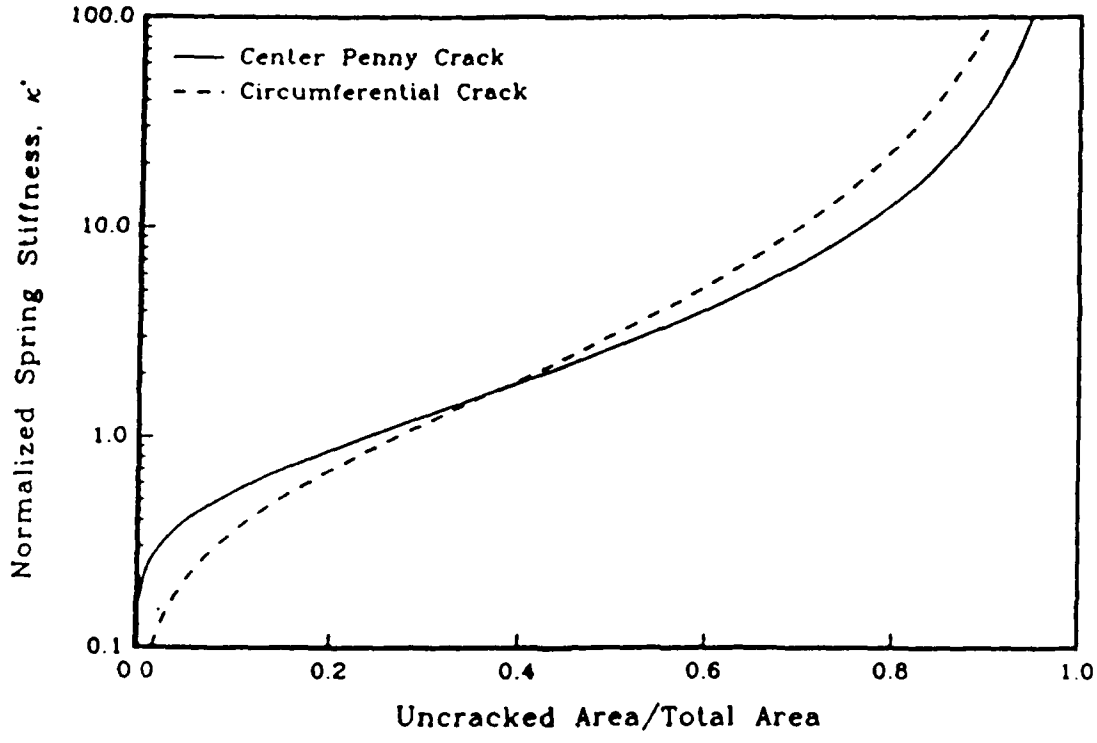
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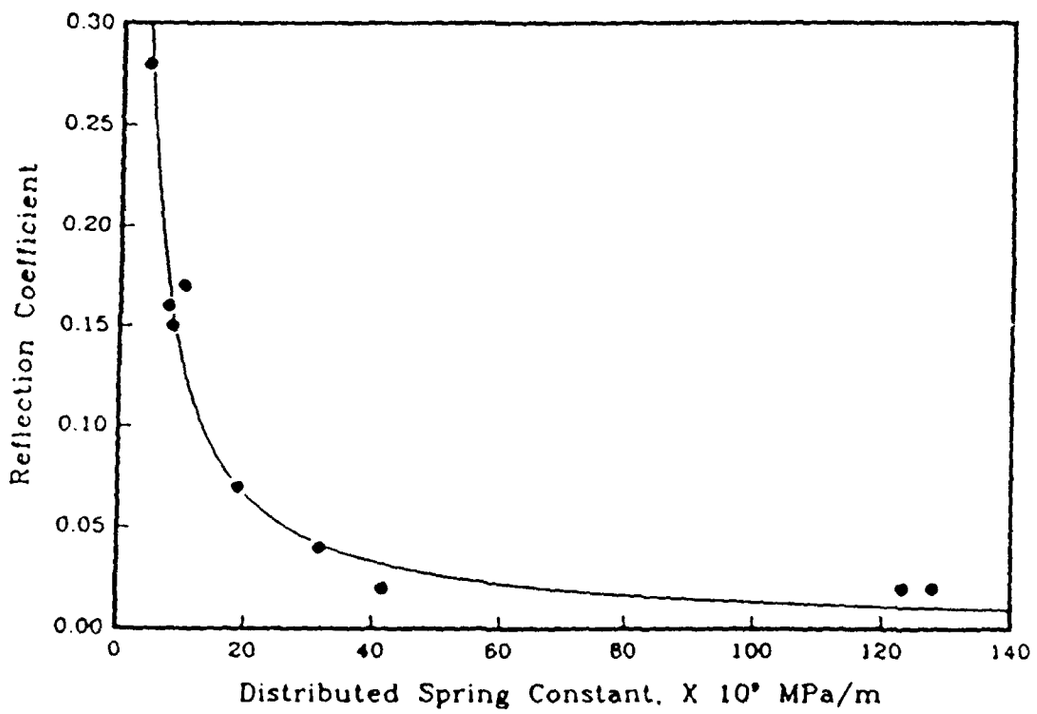
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40
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120
140
Distributed Spring Constant, X 10⁸ MPa/m

Glenn Light and Hegeon Kwun
Nondestructive Testing Information Analysis Center (NTIAC)
Southwest Research Institute
San Antonio, Texas

REVIEW OF NDE METHODOLOGY FOR ADHESIVE BOND STRENGTH DETERMINATION

The title of my presentation is Review of NDE Methodology and I was really worried that Bruce might steal my whole thunder but luckily he left off about five years ago which is nice.

We've all heard about the adhesive forces and discussions of that type of thing, I guess some important things to realize is that bonding is a very complex interaction of physical and mechanical as well as chemical properties and bonding forces. Some of the things that really have to happen is the surface must be clean, the preparation of the surfaces must be proper, there are bonds that are cohesive between adhesive type bonds which Bruce talked about a little and also the adhesive problem, which is the adhesion between the adhesive itself and the part. Another very important parameter in the whole process of bonding is the curing. I'll go over these fairly quickly because the real heart of the matter is the NDE methodology.* Some important properties of adhesion are first of all that the idea of bonding is to attach to materials. A major concern is environmental conditions, as discussed in one of the earlier talks. A major definition of what we do here is that the adhesive must be spread on the two parts or on the part and cured to form a high strength attachment and again this is important to realize it's a complex combination of various types of bonding forces. Some of the major parameters that affect bond strength are bond line thickness, the surface roughness, chemical conditions, adhesive type, humidity, aging effects. There have been various NDE techniques throughout the course of the NDE development that address several of these various properties, for example the chemical condition of the surface, the roughness of the surface. Thickness is a somewhat straightforward thing to evaluate. But the most often violated parameters apparently that appear in the real world is the surface cleanliness and dryness as well as the curing of the adhesive.

There are some reasons again for adhesive bonded structures--they are lighter and aerodynamically favorable. Cost and weight savings are there, but

*No figures are included with this transcript

some of the problems that are associated with them are the bonded area cannot really be visually inspected for defects after the bond has been made and the present state of the adhesives is that nothing seems to work very well above 300°C and almost all adhesives are adversely affected by moisture, in fact, some studies have shown that all adhesives absorb moisture over a period of time and that is the major problem of bonding.

The various types of sample structures that have been used in NDE to develop techniques are the joint metal-to-metal, composite-to-metal, composite-to-composite, honeycomb type and laminate sandwich. A very important problem associated with developing NDE techniques to evaluate the bond strength is the model used to correlate those methods and that's one of the areas where we need to do some work. How do we make samples that really have variable bond strengths and know what they are. It's fairly easy to make a good bond and a bad bond but how do you make intermediate bonds.

The NDE methodologies that I'm covering in the state-of-the-art report consider a large variety of methods and I'll go quickly over these. This covers approximately 100 papers. There's been a lot of work over the last 15 years in this area and I'll talk a little bit about each of these methods. I want to mention some of the names so that people understand who's done some of the work. I won't cover all of the names, but Rosemeier, Franking, Chang, Ye, Thomas, Adler, Bruce and Don Thompson, Klein and Klaus. There have been a tremendous number of people working on this problem. One method which isn't really listed here is NMR and that's a very recent development which we're doing some work on at Southwest Research.

Some of these methods have been applied to very specific problems and so they don't have a wide use but just for in terms of review of the state-of-the-art I'll discuss them briefly. There's eddy sonic where basically you produce an ultrasonic vibration in the joint and look at the characteristics of how that joint stays together. This primarily is for metal adherends only.

Thermography has been widely acclaimed to look at near surface type defects. One of the advantages of this is that you can view a fairly large area at a time, you get fairly good near surface resolution but the problems associated with it

are interpretation of data, the effects of surface emissivity and insensitivity to defects, because a thermal wave coming back the deeper it is of course it's absorbed and scattered more so you have less sensitivity at the deeper defects.

Optical holography and shearography have interesting near surface defect detection capabilities and I think it's a fairly good way of detecting bond strength, again a model is important. Some of the problems associated with it are that you've got to stress the material while you're doing the test so you've got to have a good stress application method and also you're interpreting fringe patterns and so you have to have a good idea of what to expect and so there's some difficulty associated with accurately interpreting the data.

Acoustic emission has been used to really be a passive type of device where you monitor bond strength as a function of noise generated and I think this has actually been applied to some aircraft structures in flight over the past few years. It really isn't a very good method for doing an active NDE test but it could be a good method of monitoring the strength of a bond.

Liquid penetrants--this is really a far out method--it has nothing really to do with very many bonds however it is a method that has been discussed. The real problem with this is that the defect problem must be associated with the top surface and that's a very rare occasion.

Now radiography has been really a very useful method in many respects. As Bruce pointed out, some of the major problems are with defects in the adhesive itself and the way the adhesive is applied. Radiography, both neutron and x-ray radiography, can be used to detect porosity, voids, excessive adhesive, presence of foreign matter, crushed or misaligned honeycomb, primarily, if you have a defect the absorption changes in the radiograph and you can see it change in that density of adhesive layer itself. The major problem with this of course is that it doesn't do very much for detecting debonds. It only detects a change in the attenuation of the x-ray or the neutron through the material itself so it detects basically a lack or excess of material. The advantages are that it's a very large field, it's fast, the problem is that you have to have access to both sides of the structure. That's sometimes a very difficult problem to do. You have to have special handling of course and you have to have film, etc. There are some

real time radiographic systems that are coming on the market today that do away with the film problem and there are a lot of advantages in that technology and real time I think is going to be an area that does help this problem.

You might be wondering why Bruce's talk considered basically ultrasonic techniques and the reason is that it is about the only method that really has a universal application I think. There have been various techniques applied--the pulse echo, threshold type of situation where we're looking for the reflection from the bonded area itself, if you have a debond you have an area interface so you get a higher amplitude, if you don't then the transmission through that bond interface allows a lower reflection. This is what I was just pointing out. If you have a good bond for example, you get a certain type of reflection. If you don't, then you get a multiple type of reflection or a higher amplitude type of reflection. This is good for detecting only good or bad bonds and it's not really very useful detecting bond strength. Through transmission does similar type things. If you have a bad bond of course you can't transmit through the bond itself but again this is a total debond or a good bond and there's not very much correlation at least that I've seen that says that you have a certain strength of bond.

The resonance (UT) takes care of a similar type thing if you have a good bond you have a lower resonant frequency of the structure because of the sandwich effect. If you have a disbond, then you see a higher resonant frequency because the wavelength is shorter. One of the methods that has shown a lot of promise is the spectrum analysis method. There've been various parameters of the ultrasonic signal evaluated. The idea is that the ultrasonic signal carries a lot of information about the adhesive area itself so people have looked at the A-scan data as well as the frequency content of that data. There've been many parameters taken from the data, some of those are listed here--peak-to-peak amplitude, frequency minimums, frequency maximums, frequency shifts, peak frequency. One paper listed 13 parameters that were evaluated and other papers have listed other parameters that that paper didn't cover so there've been many parameters pulled out of the data to evaluate. One major problem that was found with these is they're very dependent upon a transducer that you're using to take the data and if you haven't characterized the transducer very well, it's hard to pull out those characteristic effects in that data. It requires a lot of signal

processing and a lot of that technology has been developed but really hasn't shown a lot of correlation between bond strength.

I think up to this time I've kind of been catching up with what Bruce Thompson said. Now this is where some of the most recent and interesting work is. Most of the UT techniques that I've talked about up to now use longitudinal waves and go through the adhesive layer but a method to actually have a wave interact with the adhesive itself should promise a better capability of detecting the bond strength. So this method is referred to often as an interface wave, and you generate an interface wave through the adhesive and if the adhesive itself is weak, then you get a velocity change. The curing has been shown to be able to be monitored by evaluating the phase velocity. I think a major problem here, as Bruce alluded to also, is that it's hard to get through the top surface of this, how do you get the wave in and then how do you monitor the interaction of that wave with the adhesive through a top surface. This isn't really a physical situation that you see in the real world.

Another technology is called the stress wave factor where you're really looking for resonances so to speak, use low frequency and as the strength of the bond increases, you get a broader amount of energy transmitted through the bond and there's a stress factor which is represented by an equation of various parameters. This has been done for some cases and the bond strength of composite materials seems to have been a good application of this method.

Another innovative approach which has come out recently in papers is the use of horizontally polarized shear waves. You introduce the wave and it interacts with the adhesive itself and you look at the damping effect on the wave as a function of the adhesive and as the adhesive causes a reduction in the transmission coefficient of the wave. The problem here is it's a pitch catch method, you have to have a proper coupling of the SH waves in the sample, and there's some physical constraints, for example the receiver has to be smaller than the SH wave length.

The conclusions are I think, first of all, that some NDE methods can be used to detect discontinuities or problems with the adhesive itself in terms of porosity, absence of adhesive, presence of foreign material. Radiography does a

very good job of that. Some methods can be used to detect near surface, poor bonding conditions, holography and thermography, and liquid penetrant. I think the one that has the best hope for the future would be holography. Some methods can detect complete disbond versus good bond and ultrasonic methods, the L-wave type of ultrasonic methods do a good job there. I think the only real methods that have potential for detecting bond strength are the ultrasonic methods which include the interface waves, shear waves, and spectrum analysis. I think the interface wave has the most promise if we can overcome the problem of getting it in and detecting it, that will be a major area. Also I think there's a good potential for NMR. Bond weakening is caused by moisture absorption and NMR should help detect moisture over a period of time. Some work, like I said, is going on at Southwest Research. It's fairly recent work so there's not much to report on that.

That's a very quick summary. I think each of these techniques could be almost a seminar in itself and I would like to provide a better state-of-the-art review, but in 20 minutes it's somewhat difficult to cover all the bases. Thank you.

MORNING DISCUSSION
April 13, 1988

Speaker not identified:

I think the issue of strength somehow has to be defined--what are we after? What do we measure? Because there are two communities here, the people that deal with the adhesive itself and the other guys who are like us or the majority are of the nondestructive testing community. We're trying somehow to find a bridge between the two through the thing that is called strength which is really not that obvious--what actually are we measuring? Even if we had the tool to measure the strength it will be really difficult to verify those results. For reviews that were given here, most of the work that has been done in the past somehow tried to relate that to a lap shear because this is the thing, the magic word, lap shear, is the thing we should correlate with. And actually lap shear is telling us what the cohesive properties of the adhesive are rather than the adhesive property or the interface properties. So it is really important that that issue becomes clearer. To determine the interface properties, there is one quick way which is also mentioned by Bruce, the peel test where you peel the two and look at the surface. But that is a qualitative test that says yes it is good or bad, well the surface is shiny. But an actual quantitative thing where we have good, bad, medium is not there or at least not that I know. Having defects is not that critical. Structures do tolerate defects plus we have many ways of finding those defects--there's a big list of methods. We still might need new methods because there are some problems where we don't have solutions but we really have a quite wide range of methods of inspection. What we don't have is a tool for identifying the properties of the interface so I think that direction is what we should talk about mostly in terms of the strength of bonds. And again I'm not sure if I would like to use the NDE of strength as the thing we want to talk about because we really don't measure that in nondestructive testing.

Speaker not identified:

I guess from my point of view, speaking for the bonding improvement program point of view, what we mean by quantitative or strength NDE is we need a methodology that in the first place will allow us to ascertain or be sure that a

structure that has been bonded together has the strength properties required for its designed use. Beyond that we'd like to able to monitor the fall off in strength such that when it crosses below some critical value, we know that that is no longer a reliable structure for that application and we either replace it or fix it or do something to get it out of the aircraft for instance, so that it's not a safety of flight issue. That's a very pragmatic view of this but I would certainly agree that we've got to have something that addresses the interface area to really get a handle on this.

Speaker not identified:

I'd like to make a comment on the comment if you will. I think that the work that Kaelble, Knauss and Kelley did that Bruce Thompson referred to is really quite a definitive piece of work in which they recognized that the bond strength has to be defined operationally in terms of what it is you measure. And I think that's a very important thing that the strength itself is probably not a good parameter to use arbitrarily but has to be defined in terms of the measurements that you're going to pull it apart. They also recognized that even though there is such a thing as a cohesive strength, the primary dominant mechanism by far was the failure mode due to defect structures at the interface. Therefore probably a fracture dominated process or some equivalent. They also recognize that aging and so on took place via penetration of moisture in the environment effects at the edges which then permeated into these flat cracks or whatever you might want to call them at the interface. I don't mean to imply that that's the only mechanism but it certainly is a dominant one that one has to look at first and foremost. It's sort of like historically what happened to the people in the solid state physics and metals materials community. The strength of material people started worrying about the overall cohesive properties but the thing that really solved their problem was to look at when dislocations were developed and these are the real weak links in the material and really dominated the "strength" of the materials. So I think the rational suggestions that were made in the Kaelble, Knauss and Kelley report were quite to the mark of really defining a target area for future investigations on these subjects.

Niranjan Banik:

I'm Niranjan Banik of T.D. Williamson, Tulsa. First of all I'd like to comment on Don Thompson's remark that bond strength is probably not the right parameter. I would like to say that bond strength parameters may be very difficult to measure also, with ultrasonic or something else. My question to Dr. Glenn Light is how one would go about measuring the bond strength using ultrasound. As I understand ultrasound, and the conventional ultrasound especially, that includes the surface waves, leaky Lamb waves, that it will see the adhesive--metal, the surface, interface between the adhesive and the middle or other words, the other substrate is the thickness of the adhesive and I think it will be very difficult to measure the bond strength so I'd like to get a comment from Glenn Light how one would really quantify or quantitatively measure the bond strength through ultrasound.

Glenn Light:

Well, I think the recent discussion of the interface waves and the shear, SH waves, the purpose of those actually is to produce stress in the adhesive itself and so they're trying to model how the adhesive behaves under stressing. And by determining how it behaves under the stressing and the loading, they try to correlate that to a strength. The ultrasonic methods that use L-waves, I agree, don't really interact too much with the adhesive itself in terms of just giving that property. It doesn't seem to produce any physical stressing of the adhesive but from the definitions that I've seen in the papers about the interface waves and the SH waves, they're trying to correlate the stressing that is caused by those waves in the adhesive to ultimate bond strength of the adhesive itself. And if you have a poor cohesive system, that shows up; if you have a poor adhesive bond between the adhesive itself and the adherent, that also shows up, I guess in Bruce's spring model, basically it shows a change in the natural harmonic frequency of the adhesive.

Bruce Thompson:

I'll just amplify a little bit on what our thoughts were in this spring model for the interface. You can imagine a number of ways an interface might be

weak. If all the atoms are bonded all along an interface but something somehow changes the strength of that bond, you never see that with ultrasonics in my opinion because at the very weak ultrasonic amplitudes, it's still going to transmit the stress. On the other hand if you have some microscopic distribution of disbonds at the interface and certain physical processes which would lead to weak adhesion would produce such a distribution of defects, then you could hope to detect that with ultrasound and that's the purpose for this model we've developed is to try to describe that phenomena. The sphere of these interfacial wave ideas I think could be described as follows. Suppose you have an aluminum sheet and some adhesive behind it and just consider that single interface. Well if you come through the aluminum and look at a reflection you're going to get a very strong reflection anyway because it's a stress free surface and you put a little adhesive that has a low acoustic impedance, you're still going to get a strong reflection. You have very little sensitivity to whether that adhesive is there or not and what it's properties are and how it's bonded. As Glenn was saying, if you can somehow get energy in the adhesive, now this lack of bonding changes you from a rigid boundary condition that is it's perfectly stuck and those adhesive surfaces can't move much to a free boundary condition in which the adhesive surfaces can move a lot. So there's a big difference in those physical phenomena and at least has some leverage on it. So my view of it is that you can't determine strength because the overall macroscopic strength determines on defects and so forth and so forth. What you could hope to do is determine some parameters associated with the interface which is one component to strength and maybe you could reduce your uncertainties that way. That to my view is a more realistic expectation.

Speaker not identified:

I also think it's a key issue how to address a question of strength measurements and I think it's only one way to measure strength of materials simply to measure a strength and definitely you cannot measure strength directly by NDE techniques and more than this is known as a general definition of NDE is indirect techniques. So when I use NDE techniques indirectly you should know how we address specific physical parameters which we want to measure. When we speak about strengths, it's possibly good to separate two types of actually small types

of strengths as we speak of brittle fracture or simply static tensile strengths. Suppose we speak about tensile strengths of the sample. So this is key. First of all it's strength of the sample. It depends on simple geometry. If we speak about rupture sample--may be bad, may be good--convention is if it can understand what the strength of material based on strength measurements of this sample. So finally the coming to strength of material and adhesive strength measurement is not one material, it's a lot of materials, it's several materials on interface, so interface strength of oxide layer, and strength of some adhesive. So if you speak about porous oxide adhesive penetrate to this porous is going to be considered to some composite on interface and we can speak about strength of adhesive very close to this interface, so it's an extremely complicated problem. Now if we speak about ultrasonic waves, it should be understood how the same microscopic properties which affect strength of material, not sample because strength of sample is related to geometrical factors in strength concentrations. As these microscopic properties affect ultrasonically measured properties for example, there was attenuation and for my opinion it's extremely difficult to understand. For this reason many techniques show correlation, more show correlation less but finally I think it will be good to understand we will maybe have some hope to find better techniques to predict adhesive strength. So for my opinion it's because we have a lack of understanding of the actual physical parameters. It's in many cases why we have difficulties in interpretation of results.

Yoseph Bar-Cohen:

Well, I'm taking a comment from tomorrow's talk that I'm going to give in the morning. I don't want to bore you tomorrow and I will mention it today. Anyway, Professor Mal from UCLA and I are trying to look at the problem of weakness of bond and somewhat the way of quantifying this issue and looking at the bond interface, what do we have here, at least in the aerospace. If we look at the general characteristics we have either metal or composite. In the case of metal for a moment then, we have an oxide layer which is somewhat in many cases at least they cover that with an anodized layer which is another thick layer of oxide then comes a primer and then the adhesive. All that is symmetric on the other sides. The area where the thing can be weak is the area between the oxide

layer with the anodized layer and the primer because the primer itself is polymer and the adhesive is polymer so they are from the same family, they will get together somewhat pretty well. The oxide also is hard to get out from the metal. So the interface between the primer and the anodized is the area where we have to, if we're looking for clues or finding where the weakness is, I think that's the area where the weakness can come from. Now in this area a good bond at least previous experience shows that comes when we have like gripping fingers. The surface is really rough in that area where we have good grips of the two together. If this layer, this is basically a layer, that interface could be looked at finite thickness, if we could give it a value somehow as a physical parameter. Well they said that weakness is not physical, weakness is just statistic that how much stress this particular structure had been able to hold. What we are trying to do is define a parameter which is, the way we are looking at it, associated with some kind of shear module of that interface. If we have water penetrating there we have zero shear. If we have a big gap, again we have a zero shear module of that interface. Now the stages between zero and maximum shield that the interface can hold, I think that is the one way of somehow giving a quantitative measure of the quality, maybe quality is better to use than weakness, the quality of that bond--if it's higher shear coupling or shear module of that interface, it's better bond. If it's zero that means it's unbonded. And for zero of course we have many, many, methods.

Bob Thomas:

My name is Bob Thomas from Wayne State University and Dr. Light mentioned thermography in his litany of possible techniques. We have been doing a version of that for the last decade that is slightly different which we call thermal wave imaging. It's a time dependent version of IR imaging and in the last several months we've looked at some interfacial problems. I've got five slides that show some pictures of what happens when you roughen the surface and put a plasma sprayed coating on it that might bear on the subject if you don't mind me taking a couple of minutes. Three different versions of thermal wave imaging but the one I want to show you here that relates I think to some of the problems that have been discussed here, we refer to it as an area-wide boxcar averaging technique. It's much like what you do in pulse echo ultrasonics except we're

doing it in real time with fast frame grabbing. I won't go into the details because there's not really enough time to do that but I wanted to show you the problem that I think might be of interest. One of my visiting students from Helsinki brought over a section of a nuclear reactor water pipe in which they were interested in the integrity of the bond between the plasma sprayed coating, I think it's chromium oxide is what it is, onto the steel substrate. And in order to prepare the interface I guess conventionally what one does is to do a very light sandblasting of the surface in order to improve the adhesion. So the defects that they prepared, and they did 12 of these around the perimeter, were just put a very fine wire across the edge of the polished surface to interfere with the sandblasting. So you have a small region less than a millimeter in width that was not roughened and then the coating was put on and we do the following kind of variation on the infrared imaging. Basically we're setting two different gates of the boxcar if you want to think of it that way, but we're doing it pixel by pixel for the entire frame of imaging doing a series of averages on the heating curve, a series of averages on the cooling curve, judiciously choosing the time lag between the two and then subtracting. That gets rid of the problems that you mentioned in terms of variations in emissivity because everything cancels out except the time varying part of the signal. We've also done some calculations and the idea is very similar to what Bruce was talking about in terms of his springs, it's really a boundary problem. You've got the changes in thermal impedance of the two materials that will give you a reflection and then we introduce a contact resistance term which relates to that essentially zero width contact region and so you know what all the thermal properties are, you can estimate what the cooling curve should be numerically and when you do that, knowing the thermal properties of the material you get the following cooling curves for different values of contact resistance that would relate to the roughening. If you now subtract these curves which is effectively what our instrumentation does, you notice that the difference between the unbonded region and the bonded region peaks at around 50 to 100 milliseconds. So we set the gate of our imaging process there and even a manager can see that the unroughened region shows up. So I've got a lot more of those but I won't bore you with them. I just wanted to illustrate that to show that thermal wave imaging techniques I think do have some promise. In fact you can go much deeper, it's the same problem with ultrasonics, you just wait longer. In the time domain you put the energy in for a longer period of time and you wait longer to do your

averaging and processing. If you want to look at some specific interface you go to the appropriate time. The waves are very different from elastic waves, so one has to work out the theory to see which problems are most suitable but I think it does show some promise for this area. Thank you for letting me present that.

Speaker not identified:

Can I ask you a question? Bob, an important aspect of selecting applications for thermal wave imaging has to do with the conductivities and the various parameters of the media involved and here you have a two medium problem. Have you done any orders of magnitude estimates to say, is this a good geometry, that is adhesive below metal, to keep the sensitivity?

Bob Thomas:

Adhesive below a metal is not the best situation for this strangely enough. We have done some adhesive plastic and that turns out to be good but a much longer time scale. The problem with metal adhesive to some substrate is that the heat tends to flow laterally along the metal. You can still do it however. One of my former students, Gary Hawkins at Aerospace, did this on the Titan missile which is metal to a rubber to I don't know what all to the solid propellant and the time scale now turns out to be, well you heat the thing up for a few minutes with a hot water hose, you go have a cup of coffee, you come back and then low and behold the thermal reflectance is about in the right time domain. But certainly there are going to be problems for which it is not suitable as with any technique.

Speaker not identified:

In that first task study that I had mentioned there was some comment about non-linear effects and some people have done some work on nonlinear thermal wave imaging and this is directed to Bob again. Have you gotten involved in that non-linear aspects of thermal wave imaging and is there anything to study there with respect to adhesive bonds?

Bob Thomas:

I have not done that as yet. We certainly are thinking about that. Now since you are thermally stressing the materials with the heat source whatever it is, I think it's a good idea. I have not implemented it yet but I think it is a good idea because you are locally stressing the material with a heat source and then you're looking at the results of that. If you examine that as a function of power, let's imagine the electronic application where you're interested in a, let's say a thin film on a polyimid substrate, which is another problem I'm interested in. You can really cook that thing and if you look at the thermal reflectance, that R12 in my expression as a function of the DC power that you put in or the dwell time, all of those features, I would imagine you might be able to see a hysteresis in the thermal effect before you actually debond the coating. So I think that's potentially a good approach to some of these problems.

George Matzkanin:

I guess I'll ask a quick question as long as there's a lull here. I was wondering if anybody would either on the panel or in the audience care to comment on the possibility of using filler or additive materials in adhesives to provide an approach to better characterize the quality, integrity, whatever, of the bond itself. Does anybody have any feelings about the possibilities of approaches like that?

Don Thompson:

I'll try to comment. Is Bill Clark here? I saw him in the hall earlier this morning. He had a paper at our meeting in Williamsburg last summer on utilization of small ferromagnetic particles in the presence of an adhesive to primarily look at the question is there an adhesive here. And I think that's a very novel and interesting approach. I don't want to speak for Bill but I'm not sure he addresses the concept or the question of fracture or interfacial problems or adhesive properties themselves but addresses the key issue is, did an adhesive get in here and fill this up. The measurements are made by looking at as I recall the paper--this is a year ago nearly--looking at some of the resonance

properties of the ferromagnetic particle in the presence of an adhesive matrix material. They could tell the difference whether the matrix was there or not there. Please forgive me Bill if you're here if I've quoted it wrongly.

Speaker not identified:

The work that Don Thompson was referring to by the way, there was a presentation yesterday at one of the adhesive bond sessions of the ASNT conference so I know that Clark is here someplace at the conference if anybody wants to speak to him. Along those same lines, it seems to me that several years ago, there was some work by a fellow at the University of Denver, Paul Predicky* is it, on using x-ray diffraction as I recall to study the residual stresses of filler particles in adhesive layers and also in the epoxy I guess in the composite itself. Seems like that is a potential approach perhaps for studying some of the residual stresses and internal strains associated with these structures. Does anybody have any comments on that or any recollection of what happened to that particular work?

Glenn Light:

Can I change the subject for just a second? I'm not familiar with that work but I think there are some interesting analogies between what's been done with metals maybe and what can be done with adhesives and you know with metals we've many times used notches and side drilled holes etc. and we certainly got various characteristics using various NDE methods. But some of the most interesting work was when we were able to actually produce real defects in the metals, you know real cracks and real voids and that took a lot of metallurgical type of work and I think we need a model like that for the NDE community to come up with a good method to do NDE on the adhesive itself so there needs to be some work in the actual bonding chemistry I think so that real defective bonds can be made. I think we can put Teflon and we can put sprays that keep the adhesive from bonding but that's not really a real world situation unless you have somebody who's put a cigarette or something in the adhesive which has happened too. You know we need a real physical model I think to help us develop our techniques.

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*Actual spelling may be different than shown

Ken Fizer:

Since we're on the subject of real world situations, I'd like to express my concern and give the group here some encouragement in pursuing the avenues to improve our NDI methodology. We've got many secondary primarily aircraft structures out there that are in service now but they were manufactured years ago with primitive resin systems and with very poor NDI techniques to determine the condition of those particular structures. And we have some primary structures that have been in service for 10 or 15 years and they were probably inspected with questionable methods and we have no current techniques that can really give us an assessment of these structures from a structural standpoint. I mean we can go in, we can find corrosion in honeycomb, certainly and we can find disbonds but the precursors to those conditions we are not able to inspect for and it's only a matter of time before we're going to have some sort of crisis that we're going to need these technologies and these weapons in our NDI arsenal before we can really attack the problems at their source and identify those components and materials that are about to fail.

George Matzkanin:

One of the questions that was posed on one of the forms here I think follows up this last comment. This puts it in a nutshell to some extent. The question was "What efforts are required to enable the determination of bond strength through NDE on a production basis?" Seems like I guess if we answer that we've done it all. The person says a flexible system is desired, that is one which can interrogate large area bonds such as honeycomb core sandwich panel wing skins and so forth, as well as long durobonds such as wing skins spar bond lines so if anybody has the solutions to that problem I guess that will take care of a few things.

Don Thompson:

Of course that's really why we're here and what this Workshop is about but the converse of that is in the absence of that methodology, we're not going to get extensive use of adhesive bonding in primary structure on aircraft and we

will therefore lose the advantage that accrues to using this joining technology. That's why we have identified quantitative NDE as one of the real pacing problems in the effective use of adhesive bonding in Army systems.

Robert Bonk
Organic Materials Branch
U.S. Army Armament Research, Development and Engineering Center
Picatinny Arsenal, New Jersey

CHARACTERISTICS OF ADHESIVE BONDS: ADHESIVE BONDING/JOINING

My topic today will be adhesive bonding and joining. It will be a general description. I'd like to begin with a definition of a joint: the union of two members for the purpose of transmitting loads from one to the other.

When and where shall we use joints? When it's impossible or impractical to fabricate them in one piece, when you have to disassemble or mounting is required, to restore the item to service after it's been broken or failed. There are two types of joints, mechanical and adhesively bonded ones. Mechanical joints employ mechanical fastening or fasteners such as nuts, bolts, pins, rivets, crimps, detents, etc. They often require machining and drilling. You drill with a machine and you're introducing stresses. The load transfer is due to bearing stresses. The pros and cons of mechanical joints. The technology is straightforward, there are no unusual skills or knowledge required, repeated assembly and disassembly is allowed and there's good quality control. The disadvantages are stress concentrations are heavy, there's no sealing of the environment to the exposed surfaces, galvanic corrosion, possibilities of dissimilar materials, and it's poor in aerodynamic flow characteristics.

The second type of joint is an adhesive joint. It depends upon surface phenomena. It relies on surface chemistry and chemical reactions. The technology is complex. The mechanism is not fully understood and controlled. A knowledge of the adhesive theories can assist in understanding the basic requirements. It's highly reliant on processing, strict training is required. The advantages and disadvantages of the adhesive joint are as follows. It's lightweight, the strength-to-weight ratio is very attractive, there are less stress concentrations, there's no machining or damage to the substrate, possesses good insulating qualities for heat transfer and electrical conductance, it offers galvanic corrosion protection, and it's naturally sealing to the environment. The disadvantages are it's process dependent; special skills are needed, training, it's hard to inspect for quality visually. The life and type of the

CHARACTERISTICS OF ADHESIVE BONDS: ADHESIVE BONDING/JOINING

R. BONK

13 APRIL 1988
WORKSHOP ON NDE OF ADHESIVE BOND STRENGTH

WHERE/WHEN TO USE A JOINT

WHERE/WHEN:

- IMPRACTICAL/IMPOSSIBLE TO FABRICATE ITEM IN ONE PIECE
- DISASSEMBLY/MOVEMENT REQUIRED FOR ACCESS, REPAIR, OR MAINTENANCE
- TO RESTORE ITEM TO SERVICE AFTER BREAKAGE/FAILURE

CLASSES OF JOINTS

- MECHANICAL
- ADHESIVE BONDED

MECHANICAL JOINTS

- EMPLOY MECHANICAL FASTENERS
  - NUTS/BOLTS
  - PINS
  - RIVETS
  - CRIMPS/DETENTS
  - INTERFERENCE FITS ETC.
- OFTEN REQUIRES MACHINING/DRILLING
- LOAD TRANSFER DUE TO BEARING STRESSES

joint fixturing, surface preparation, attack by bacteria, mold, rodents, etc. are a big disadvantage. Disassembly of a bonded joint requires destruction.

The adhesive works in the following ways. It must be liquid to flow and to wet the surfaces, it must solidify, it can solidify through solvent evaporation, heating then cooling or through chemical reactions. The adhesive must be capable of transferring loads.

There are three types of failure modes in adhesive joints. The first is cohesive failure, which is an ideal type of failure for bonding. The rupture occurs within the adhesive. The second type is adhesive failure and the rupture occurs at the adhesive-adherend interface. The last one is substrate failure where you have your failure in your substrate whether it be metallic or plastic or whatever.

There are different approaches to obtaining a design. I've broken these down into two phases. However, before you go into this it's important to know whether your joint is going to be bonded or mechanically fastened. All too often a joint is designed for mechanical fastening then it's altered slightly for adhesive bonding. The outcome of this is a disaster. Phase I of the design approach offers loads to be transferred. What are the magnitudes of these loads, the types, shear, tension, compression, the mechanical properties of the joint members involved, the thermal conductivity of the joint member or members, the chemistry of the joint members, service requirements. I put these all into compatibility--temperature, humidity, explosives and propellants which I deal quite a bit with in my group, gasses, chemicals, radiation, fungi, surface life, manufacturing limitations, facilities and personnel. These are very important. You need strict training and people should be trained. I don't believe there are any training courses available. Picatinny does offer one but you have to come in to Picatinny for a job.

Our interns usually go through a training program, it used to be 80 hours, now because of funding limitations, I believe we're down to approximately 20 hours. In 20 hours you can't learn too much, in 80 hours you can't learn too much. But you do need training.

ATTRIBUTES OF ADHESIVE JOINTS

PRO

- LIGHTWEIGHT
- LESS STRESS CONCENTRATIONS
- NO MACHINING/DAMAGING SUBSTRATE
- INSULATING
- CORROSION PROTECTION
- NATURALLY SEALING

CON

- PROCESS DEPENDENT
- SPECIAL SKILLS NEEDED
- HARD TO INSPECT FOR QUALITY
- DISASSEMBLY REQUIRES DESTRUCT

THEORIES OF ADHESION

MECHANICAL THEORY

- ASSERTS THAT ADHESIVES FLOW/FILL SURFACE CREVICES CREATING A TYPE OF CAST MECHANICAL FASTENER.
- CONTRIBUTION OF SIGNIFICANCE IN BONDING POROUS SUBSTRATES
- SMOOTH SURFACES SOMTIMES ROUGHENED TO:
  - SURFACE AREA
  - DIRT
  - SURFACE REACTIVITY
  - MECHANICAL LOCKING

DIFFUSION THEORY

- POSTULATES ADHESION RESULTS FROM INTERDIFFUSION OF ADHESIVE AND ADHEREND MOLECULES
- APPLIES WHEN ADHESIVE AND ADHEREND ARE BOTH POLYMERS
- EXAMPLES ARE SOLVENT OR HEAT WELDING OF PLASTICS

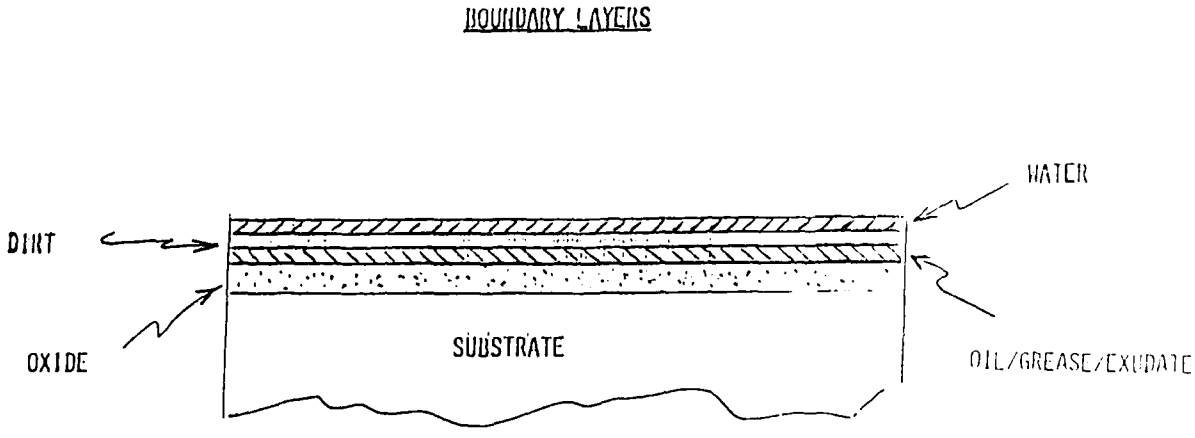
ADSORPTION THEORY

- ADHESION RESULTS FROM MOLECULAR CONTACT BETWEEN 2 MATERIALS WHICH BRINGS SURFACE FORCES INTO PLAY
  - LONDON'S DISPERSION FORCES
  - ELECTROSTATIC
  - COVALENT
  - METALLIC

WEAK BOUNDARY LAYER THEORY

- NOT REALLY A THEORY OF ADHESION BUT OF HOW BONDS FAIL
- ASSERTS THAT ALL ADHESIVE BOND FAILURES IN WEAK BOUNDARY LAYERS
  - OXIDES
  - DIRT/OIL/GREASE
  - LOCALIZED SURFACE IMPURITIES
  - LOW MOLECULAR WEIGHT POLYMER CONCENTRATIONS

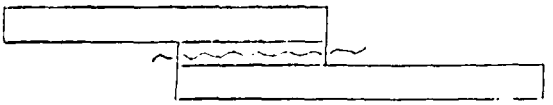
WHAT DOES ADHESIVE SEE?



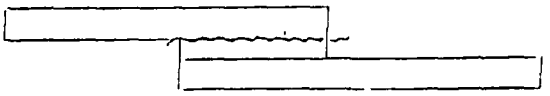
HOW DOES ADHESIVE WORK?

- MUST BE LIQUID TO FLOW AND WET SURFACE
- MUST SOLIDIFY
  - SOLVENT EVAPORATION
  - COOLING
  - CHEMICAL REACTION
- MUST TRANSFER LOADS

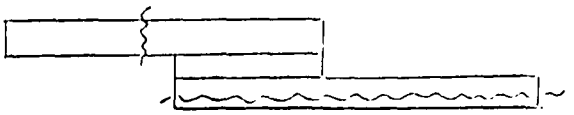
FAILURE MODES



COHESIVE FAILURE



ADHESIVE FAILURE



SUBSTRATE FAILURE

DESIGN APPROACH

PHASE I

- LOADS TO BE TRANSFERRED
  - MAGNITUDE
  - TYPE (SHEAR, TENSION)
- MECHANICAL PROPS OF JOINT MEMBERS
- DTCE OF JOINT MEMBER
- CHEMISTRY OF JOINT MEMBERS
- SERVICE ENVIRONMENT
  - TEMP/HUMIDITY
  - EXPLOSIVES/PROPELLENTS
  - GASES
  - CHEMICALS
  - RADIATION
  - FUNGI
- SERVICE LIFE
- MANUFACTURING LIMITATIONS
  - FACILITIES
  - PERSONNEL

Maintenance requirements. Is disassembly required for the joint or the design? Damage and part replacement. These I've put into field repair. How is the damage going to be repaired, how are the parts going to be replaced? Phase II of the design approach is to select whether you're going to mechanically fasten or you're going to adhesively bond the part. Don't alter the existing mechanical method to fit the bonded. The design configuration. If bonding, identify the processes. Surface preparation--very important. Type of adhesive you're going to use. Cure conditions--another one that's very important. Quality control, quality assurance--you should test the joint and if modifications are needed, modify that joint, test it again, then finalize your design and fabrication processes.

Bonded joint testing. Use the following methods here when you're designing your joint. Simulate the stress mode in the end use. In other words, what is your end item going to be so induce those stresses, test in that manner. You need a reliable and reproducible method. People usually use a single lap joint, not too good. Use the simplest possible machining fixturing approach.

Commonly used adhesive test methods, all destructive methods, ASTMs, shear, tensile, peel, etc. Nondestructive testing cannot predict the bond strength as yet. It can identify voids and disbonds and it's most useful for quality control.

And finally, avoid using joints if you can. If you have to join two members together or more, determine whether you're going to mechanically join them or you're going to adhesively bond them. Go and design your joint, employ a rigid approach and develop design rationale. I'd like to add here also, Dr. Wentworth mentioned this morning about Mil Handbook 691B, very helpful, and it would give you more information as far as adhesive joining, designing and such. Also something that I'm involved with, not that heavily anymore, is the adhesive data base which has been generated by ARDEC, Picatinny Arsenal. We do have various adhesive systems in there. We have laboratory data, we have design for manufacturing data, lessons learned, as Stanley mentioned this morning, there's a whole gamut of information available there. As of yet, it's not available to private industry. You can get into it if you're a government agency. The people to contact if you're interested in this data base are Joe Bresha at ARDEC or myself and we'll be glad to give you whatever information that you require. I thank you.

DESIGN APPROACH (CONT'D)

PHASE I

- MAINTENANCE REQUIREMENTS
  - IS/IS NOT DISASSEMBLY REQ'D
  - DAMAGE REPAIR (HOW)
  - PARTS REPLACEMENTS (HOW)

PHASE II

- SELECT MECHANICAL VS. BONDED
- DESIGN CONFIGURATION
- IF BONDING -- ID PROCESS
  - SURFACE PREPARATION
  - ADHESIVE TYPE
  - CURE CONDITIONS
  - Q.C/Q.A.
- TEST THE JOINT
- MODIFY
- TEST AGAIN
- FINALIZE DESIGN AND FABRICATION PROCESS

BONDED JOINT TESTING

- SIMULATE STRESS MODE IN END USE
- RELIABLE/REPRODUCIBLE RESULTS
- SIMPLEST POSSIBLE MACHINING/FIXTURING

COMMONLY USED ADHESIVE TEST METHODS

TYPE TEST	TEST METHOD	
SHEAR	SINGLE LAP	ASTM D1002, D31 D3164
	DOUBLE LAP	ASTM D3528
	COMPRESSIVE	ASTM D2182, 175 905
TENSION	BUTT TENSILE	ASTM D897, D20
PEEL	180 PEEL	ASTM D903
	T PEEL	ASTM D1876
	CLIMBING DRUM PEEL	ASTM D1781

NON DESTRUCTIVE TESTS

- CANNOT PREDICT STRENGTH (AS YET)
- ID VOIDS/DISBONDS
- MOST USEFUL FOR Q.C.

SUMMARY

- AVOID USING JOINTS IF POSSIBLE
  - VIEW AS DAMAGE/AN INTRODUCED DISCONTINUITY
- IF MUST JOIN
  - MECHANICAL
  - BONDED
- DESIGN JOINT
  - EMPLOY RIGID APPROACH
  - DEVELOP DESIGN RATIONALE

Hal Brinson*
Center for Adhesion Science
Virginia Polytech Institute
Blacksburg, Virginia

TEST SPECIMEN GEOMETRY FOR DURABILITY PREDICTION

Center for Adhesion Science (CAS)

One of the things George Matzkanin asked me to do is to tell you a little bit about the Center for Adhesion Science at Virginia Tech and so I thought I would take a few minutes to give you a little propaganda about our University and our Center and then he also suggested that I have a technical flavor to the talk and I thought perhaps I could tell you a little bit about some of the things that we're trying to do there and how we're going about doing it. Before I get started, let me do this. I brought some information with me. There is a brochure of our Center here, I left a few copies out on the table outside and I don't know if there are any left or not. If there are, feel free to pick them up. I only could bring a few so if you'd like to have one, drop me a note at Virginia Tech and we'll put one in the mail and get it out to you.

Some other propaganda is that this year we are putting on a Workshop that will occur the first week in May; we have one annually the first week in May. There's a little flyer out there about that. We have an excellent program and we'd be glad to have some of you consider coming down for it. So you can pick that up as well and again, if they're all gone and you'd like to have one, drop me a note. It starts on Sunday, May 1 and goes through Wednesday. Also there's a little flyer out there that last year we had a Workshop the first week in May and we took the papers from that Workshop and bound them into a Proceedings type of volume and it's called Adhesion Science Review. We're selling those and we'd love to sell each and every one of you a copy. It's only $40 and it's got a lot of good science in it. Again if you'd like to have this drop me a note.

Now a little bit about the Adhesion Center at Virginia Tech. We were founded in 1982 with funds from the Office of Naval Research. Dr. Larry Peebles was instrumental in having this money flow to us. We wrote a proposal in competition with about 13 or 14 other universities around the country and were awarded the contract. One of the principal reasons as I found out later is that

*now at University of Texas at San Antonio (UTSA)

if you looked at these four founding members, Dr. Dwight, Ward, Whiteman and myself, that many of us had interactively worked together. You'll see that Dr. Dwight was in the materials engineering department. He was mostly you might say a fractographer, someone who did ESCA and Auger and scanning electron microscopy. Dr. Ward is a polymer chemist, Dr. Whiteman is a surface chemist, and I'm supposed to be a mechanics person. The whole idea was to bring chemistry, materials and mechanics together in a concerted fashion to examine adhesion science in a way that people had not done before. In other words, it was supposed to be an interdisciplinary program in which we not only did our own thing and told others what we did, but we tried to learn from each other and incorporate their science into our science.

Now as you might know, this is a very difficult thing to do and in fact, if you take old dogs like us, it's probably more difficult than it is with the young people. So, part of the focus is in fact on an educational program where we take young students, Ph.D. students, or Master students and try to get them to work in an interactive fashion. We have just turned out two Ph.D. students, Dr. Whiteman turned out a student that many of you may know, Dr. Janet Pillbenow* who was a very outstanding surface scientist and Dr. Ward turned out a polymer chemist, a very outstanding guy, Dr. Paul Koning*, who is more or less a polymer chemist, and we have one in my lab that's about ready to go. He could have gone a year ago but he's just dedicated, Didier Lefevre*. If you look at these people and talk to them, I think you will be absolutely amazed at how much one can do in this regard. So we feel that we are in fact creating a new generation of people that will have a different prospective on adhesive bonding. So we hope we're following through on that purpose that is at the bottom of that transparency.

In terms of the people that are involved in the Center, we have the Chairman, myself, we have a full-time administrative assistant provided by the University which is actually a pretty good deal. We have two part-time secretaries that we employ, and we have two adjunct faculty. These two adjunct faculty are faculty that are affiliated with the Center by and large. We have about 15 other faculty that come from three colleges and nine departments that affiliate with the Center. Each of these 15 faculty have a sponsored program with some aspect of adhesion science involved. If you add up all the dollars involved there it's probably, well it's hard to get a number but it's certainly

*actual spelling may be different than shown

over $2 million, it may be closer to $4 million, I really don't know. But there's a lot of activity on the campus with faculty working in the area of adhesion science. There are about 13 or so other faculty who have very closely related activity and in fact some of them are here, Dr. Duke, Dr. Henneke, Dr. Reisnider, and Dr. Stinchcomb. All of these people do excellent nondestructive evaluation. I'm not aware that they have any particular project on adhesion science right now, but certainly they are there if we need to look at flaws or that kind of thing. We have the capability of doing those things, in fact we'd love to have them working on those particular projects. I did find there's a former student, a fellow who graduated, got his BS with us a few years ago, who's in the audience. In fact, he did his senior thesis on an NDE procedure with Dr. Duke. So we're putting people into the workplace.

The number of students that you see there is pretty accurate.* If you total the graduate students, it's close to 60 or so that are working on adhesion related projects. They are getting degrees however in departments like chemistry, mechanics or materials, or in an interdisciplinary Ph.D. program materials engineering science. We have several courses that are specifically tailored to adhesion science. Tom Ward, Jim Whiteman and myself team-teach a course each spring on adhesion science and in fact it's going on right now. We've been extremely gratified with this course because when we first put it in about five years ago, when we first announced it, we went to the appointed room thinking that well, we might get half a dozen students to come in, our own students you know, to take the course. We were just absolutely amazed because the room was full, there was standing room only. In fact there were people standing that couldn't sit. There were something like 50 people there. And most of those were freeloaders but I think 25 or so actually registered for the course and that's been the trend for the last five years. In other words, the point is that there seems to be a genuine interest on the part of the students at the university in learning more about this area of adhesion science--much more so than we anticipated.

There are some other courses. A colleague of mine, Dave Dillard, teaches a course in mechanics of adhesives and then there are surface science courses and polymer science courses that are certainly applicable. We have a short course that we teach occasionally; we've taught it off campus a couple of times. We

*No figures are included with this transcript

have an excellent seminar series and we'd love to have somebody come down and give us some outstanding information about the NDE. We have this annual program review or workshop that I mentioned earlier and then we have employment opportunities through co-op and other programs.

Now just to sort of summarize where we are. The Navy started the funding with us in 1982 and that program has brought in a lot of funding for a number of faculty and graduate students and is in the process of being phased out this year. It was kind of a center of excellence grant and the idea was that we should become self-sufficient and find other avenues of support. Fortunately, about the same time, the adhesive and sealant industries were interested in creating an academic center and they've gone through a process of identifying universities that would house or be the host institution for this academic center. And just last spring the Adhesive and Sealant Council announced that we would be the host institution for this academic center. They're in the process now, the Adhesive and Sealant Council, of raising approximately a $5 million endowment for the Center. I might just say that the Adhesive and Sealant Council, if you're not aware of it, is a trade association. It's a consortium of something like 200 plus adhesion companies. Just to give you a point of reference so that you understand the commercial side of adhesion or adhesives and sealants, there are about 10 billion pounds of adhesives made in this country annually, and if you think of how little adhesive it takes to glue something together, that's a lot of glue. Ten billion pounds, about $5 billion a year market. There are 200 and some companies that have joined together to promote the area and are raising this endowment.

Now what you see here, these are some of the industrial affiliates that we've had over the years. We've had on the order of nine or ten and you can see some of the ones that we have there. If there are any companies out there that would like to affiliate with our Center, we would be pleased to have you do so and we will give you all the financial details.

This is just a little breakdown on the income that we expect to receive from that $5 million endowment. When it's in place, it will be on the order of about $275,000 a year, maybe $300,000 a year and that will be just the income from the endowment. We really anticipate that there will be probably double or triple

that in other ways by direct research contracts, consulting and other kinds of activities. What we've identified that we will do with most of the money is to fund students, roughly 24 undergraduate scholarships and about 15 fully funded graduate students, meaning that we pay their stipends and their tuition and fees and everything, it's a free ride. And then there are some other things that we have planned.

Now there are several things that are going on on campus that are rather exciting and one of them is actually in the organization of our materials activities on campus. One of the things that's been done recently is we've created a Materials Institute. Dr. Jim McGrath is the Director of this Materials Institute. Under this Materials Institute which operates out of the Provost Office, there are other activities, meaning the polymer activity, the composites activity and the adhesion activity, and then perhaps other materials activities as well. So there's the beginning of a coordinated effort on campus to focus on the various material activities.

Another thing that has just recently come into being is that the three groups of people, the polymers, composites, and adhesives people have gotten together and submitted a proposal to the State Council for Higher Education in Virginia which is the top education office in the state. And we are to receive funding from them if all the rumors are true, to create a commonwealth center on materials and this will be called the Virginia Institute for Materials Systems and this is going to be directed by Dr. Ken Reisnider and again, under that, there will be a polymer science directorate with the people that you see there, an adhesion science directorate and a composite science directorate. Then the really exciting thing is if you look at the totality of effort at Virginia Tech in the polymer based materials area, you'll see we have an enormous amount of capability and these are just some of the capabilities, it's not complete by any means. I'm sure I've left people out and if there are some here in the audience, I apologize already. You'll see that we have synthesis, polymer characterization, morphology surface science processing, NDE, mechanical characterization, durability, mechanics analysis, finite element analysis and so forth. The point is that we have a huge group of people with a huge graduate student population. There are probably 50 or so faculty who are working in these areas. There are probably 200 or more graduate students and enormous sums of

research funding and so we literally can take a material from the synthesis stage all the way up to the design stage and do all the investigations necessary. The idea of this commonwealth center is in fact to have again an interdisciplinary program where we're looking at specific material systems such as adhesive bonds or composite materials to be able to educate people better and to understand the science better. That's really what we're doing.

Now I'm going to stop with that because that's probably more propaganda than you wanted to hear anyway and go on now with the more scientific aspect and I hope I'm not going on too long.

Discussion of Adhesive Bonds

Now just to follow up the previous speaker, let me say that whether we have bonded joints or not, we do have major concerns with adhesion science virtually everywhere. I've brought along a few examples to show you and you can sort of pass them around but I'm a university Professor so there's an examination after this and to successfully complete that examination, all of you have to return these things to me. You can't take them away with you.

The first thing I'm going to show you is actually a section from an aircraft, it's the Fokker F28, the Dutch plane that many of us in Blacksburg fly because Piedmont uses that plane and flies out of Roanoke all around. This plane is made with an all bonded construction and what they do is they laminate sheets of aluminum much like you do plywood and the whole plane is made that way. It's been in the air for 30 years now and they claim no failures due to bond failures. So therefore it's not a joint exactly, it's a technology where you manufacture things by using bonding. So you take a look at this and then you'll recognize the importance of adhesive bonding in this one application.

Now the other is of course something that all of you would recognize. This is a graphite epoxy tensile bar that we worked on a number of years ago and we have a lot of activity at Virginia Tech on these. I brought this along for several reasons. Number one is if you look at the test specimen it's got end tabs bonded to it so we use this in our test methodology and this is important that those bonds work properly. But in addition to that, if you begin to look at this, we had some problems with these specimens, actually in the machining stage

and it turns out they delaminated. You can do that, please be gentle, don't break my specimen in half. But you'll see how it has delaminated. That is an adhesion problem so there's fiber matrix adhesion and interply adhesion. So everybody wants to go to composite structures and then you see what the problems are.

And then finally I have a tensile lap joint that I brought just as an illustration and this is one in which we embedded a strain gage so we can measure axial strains. Some would say you can't do that but we can and we can talk about it if someone's interested. But that's the lap joint that somebody talked about a few minutes ago. We'll come back to that.

The idea now is to talk about some of the needs that we have and one of the most pressing needs in adhesion science is the development of test specimen geometries. Now that sounds rather dumb but as we go on I think you'll understand what I mean. The methods by which we evaluate adhesive bonding are not good and we need to improve those and this has been a focus of some of our attention there. What we're really concerned with is durability and of course we have to understand what we mean by durability. We can look in the dictionary and find what Webster says about durability and that usually means that something will last a long time, something like that. What we mean here is more in the sense of structural durability, meaning that it not only lasts a long time but it serves a structural purpose, meaning that it carries stress and it performs a structural function for a long time. Of course what you'd like to be able to do is predict durability. How do you go about predicting durability? Now many of you probably with companies have already examined this topic and it's been a big topic in metal technology for many, many years. The fundamental thing that people look at for metal technology is fatigue. Now as you cycle a metal or you bend it back and forth and you all know that eventually it will break. So there's been a whole technology related to fatigue that has been built up over the years, especially with aircraft structures, to understand how to assess the durability related to fatigue.

There are other aspects like corrosion and so forth but that's a principal one, it's done largely on fatigue crack growth and other things like that. Now, polymers and polymer science came along and durability has a different role for

polymers, or means a different thing. You still have fatigue, you take a polymer and you fatigue it and you know that you can break it. That's one thing. But you also know that if you do a relaxation test, meaning that you suddenly stretch it that the stress decays, meaning the modulus changes, the property changes. Or if you do creep, the thing will creep. The property changes as a function of time, that's durability too. In other words, it's not doing what it would do in the beginning if those properties are changed. So therefore, polymer has two kinds of durability. It has the fatigue, like a metal but it also has this fading memory like a polymer. Then you go to an adhesive bond and the adhesive bond has another one. It has the interface. And there are things that happen at the interface that compromise durability. So therefore you have a threefold effect with adhesive bonding. You have the fatigue, the fading memory, and interfacial and corrosion effects. So you have to worry about all three. Now those of you in composite materials will be happy to know that you have all of those in composite materials. So if you want to look at it that way, probably a composite is the most complicated structure but on the other hand, an adhesive bond is a composite structure by definition.

Now how do you go about assessing durability for adhesive bonds. This is sort of a standard technique. There are several experimental apparatuses that people use, one of them is the Alcoa Memford Ring, this is the so-called 3-M durability tester and what they do is they take a single lap specimen that you see in the upper right corner there, they take a chain of these and put them together on a chain, put them in a little cylindrical device with a spring on the top, you compress the spring which tensions the chain which means you stress each one of those single lap joints. Then you take the whole device and put it into a temperature/humidity cabinet and you essentially wait for it to fail. It'll break after a certain period of time. What will happen is if your stress is high, and this is the average shear stress, meaning that you simply take the load and divide by the area of the bond, then you come up with an average shear stress, if that load is high it takes a short time to fail, if it's low it takes a long time to fail. And then you can try to come up with some sort of endurance limit meaning that below that level it never fails. That's one approach to durability of adhesive bonds.

Now I might just say that this single lap joint is a really good vehicle to emphasize the need for NDE. One of the things that we need to do is when we make a joint like this we need to be able to inspect and see what kinds of flaws there are. It's a very challenging problem and I heard the previous speaker say this is something we can do and it's true that with a single lap joint or even big panels on aircraft or other places, you have techniques where you can identify flaws. Normally though these flaws that you can identify, the big ones are out where they don't matter, they're out in the middle of the joint, it's hard to get the air out. If you put two things together there's air entrapped in there, and it's hard to get that air out of the middle. It turns out though that the stress field in that region is virtually nil. Therefore, you've got a big flaw but it doesn't matter, there's no stress anyway. Now out near the edge of the specimen, out near the edge of the adhesive you can get the air out, so therefore any flaws you have out near the edge will be relatively small. But you need to identify those because that's a very high stress field. The stress gradients there are extremely high, you have very high peel stresses, very high shear stresses. So the small flaw in a critical place is much worse than a big flaw in a place that doesn't matter.

Then you have the other thing that's probably even worse, we have a tremendous language in adhesion science. I love it, we talk about kissing bonds and intimate contact and all those things. So you ask the question, can you find a kissing bond, that means that you have the adhesive next to the substrate and it's in intimate contact, that means that it's right together, there's no space, no gap, no air. Can you find that if it's small? Or even better still, and the FAA has been funding a program like this with GD for some time, can you find a weak bond? In other words, suppose you have the bond actually in place but it's just not very strong and if you have a weak bond out in a high stress gradient region, that may be much more severe than a big flaw out where it doesn't matter. So those are the things that you really need to detect. That, I think, will stretch your imagination to be able to do that. This comes back to something that Bob Schlikeman* of Fokker said to me when I was visiting a few years ago and it would be a theme to your heart because he said that in designing adhesively bonded aircraft structures that if you cannot inspect it, you cannot fly it.

*actual spelling may be different than shown

So these are some real challenges that you have to look at. This emphasizes some of the things you need to do, or we all need to do. Now to get back to the story though, if we take the results of a test like this and plot them, what we usually do will be to plot a bar chart that looks something like this and what we see here is we see single lap joints that have been tested and this is titanium now. The titanium in each case was pretreated with various kinds of techniques. In one case with PF or phosphate fluoride, if that single lap joint was put into the durability tester, it failed after just one day. So that's not a very good surface pretreatment. Then we took Turco, this is work of Dr. Jim Whiteman, and pretreated the titanium with Turco, and then we did the test again and you see that it took between 12 and 28 days for it to fail, so that's a better pretreatment. Then he took chromic acid anodized and treated the surface and lo and behold you get the best of all and it's 24 to 48 days. So therefore obviously you would want to anodize with chromic acid and you would get better results.

You might just take note of one thing. If we go about doing an analysis, like a finite element analysis, to design the aircraft, how do we go about doing that? Well, to do the finite element analysis, we have to have properties. We put properties into the finite element code. The code does not generate properties, we have to measure properties and put it in. Now what properties are typically put into codes? You test the metal, the titanium, you get the properties of it--strength, modulus--put it into the code. You take the adhesive, like the bulk resin if you want to and make tensile bars of it to power it, you put that in the code. Or you could even test bonded joints and get a cohesive failure and you put that in the code. That sounds great, the only problem there is you don't put the right thing in the code because how did these specimens fail? They were all made exactly the same, the same metal, the same adhesive, what was the difference? Pretreatment. That didn't go into the code. It's not in there anywhere. So therefore the one thing that causes the failure is not in there, the durability failure. So we need methods by which we can evaluate that and put a number on it and that's one of the things that we're trying to do. Now, there are other techniques and I'm not going to take time because George would throw me off the stage but you can use the Boeing wedge test to evaluate durability if it is very great. It's a peel test though and some people are worried that it doesn't evaluate shear. So consequently, there's a

big emphasis now in a number of areas to come up with test specimen geometries where you can actually look at both shear and peel and come up with good values. These are some of the specimens that people are looking at. The one at the upper left is the so-called Tosupeskey* specimen which is a four-point bending specimen but you get pure shear at the bonded area and the idea then is you can just take "p" over "a" and come up with a good value for the stress and you can also put tension on it, you can get combined loading effects. The specimen on the right is called the Arcan specimen and you can do the same kind of things, the bond is right there in the middle of that key slot between the two key slots and you can do the same thing there. You can just calculate the shear stress by "p" over "a" or you can put biaxial loads on it. Another specimen, torsional specimens, one that colleagues worked on, Dr. Grant, is a Coning Plate specimen and then there's another one down in the righthand side that I'm sort of partial to, it's one that we've looked at a little bit. It's a cantilever beam specimen and the idea is the following: that if we take a cantilever beam.....

NOTE: (recording difficulties, portions of talk not recorded)

.....then we come along if we took a solid beam there's no adhesive at all. We load it on top and bottom, we would get the bottom curve. Now suppose we put adhesive in between. Well you can visualize that that would be somewhere between the solid material and the no material. And so we can actually come up with a coefficient of adhesion this way but what will happen is that because you're pushing down on the top and pulling down on the bottom, you induce a state of pure shear, absolutely pure shear. Some of you mechanics guys will say it's not so, but it is so and we can argue about it if you want to. There's no argument really because what we'll do is show you that if we plot the distribution of shear stress with the length of the beam, you get something like this. Some of you have learned in your mechanics that the shear in this kind of beam is uniform from one end to the other, it's not so. It varies as you see here. The maximum value is out at the free end and the shear is actually zero at the cantilever end, in the adhesive. Well that's a little bit strange but we can tell you about that too. The really important thing about the beam though is that if you look at the end where the shear stress is a maximum, that it turns out that under certain conditions, you can calculate that shear stress without knowing the properties of either the adhesive or the adherent. In other words,

*actual spelling may be different than shown

the stress determination is independent of the material properties and that's what's needed for a good test, that your properties are part of the test is the problem. So consequently you can do that and just to prove that we know what we're doing, we think, this is a comparison with finite element results and finite element results gives exactly the same thing. Don't try to do this with the theory of elasticity because it won't work, but we will talk about that another time.

To show you essentially what we're driving at is the following. What we can do now is we can take a specimen like this and we can say if we take a cantilever beam, if we pull in opposite directions, that's mode one. We all know that, that's the Boeing wedge test, it's mode one, so we can get mode one fracture values very easily. We can push in the same direction on top and bottom, you can get mode two, that's nice, pure mode two. And if we use different magnitudes, you get a mixed mode, so therefore we can get pure modes or mixed modes out of this as we wish and we can look at fracture values. Now, more importantly, we can put that into a device and this is sort of a schematic of a device that we could use. We've done this a little bit but not nearly as much as I'd like and if you got lots of money, we'd be glad to take it and do some more of these things. We have an electrochemistry apparatus where we can put a zinc anode inside, we can alter the PH, we can bubble oxygen into it, we can do all kinds of things to vary the electrochemistry and to get various penetrants to diffuse into the bond. Then we can begin to investigate those things, those are the things that cause durability failures. Then we can begin to measure both mode one and mode two fracture properties and so forth.

Probably even more important than that and I don't have time to spend on it, is to see if we can find a method by which we can actually evaluate properties. The idea fundamentally is the following: that we would like to have a method that would be microscopic in nature, meaning that we could look within the bond line and look say in the middle of the bond and try to measure the property of the adhesive in that bonded state and then progressively move close to the interface and measure the property near the interface. So if we combine this with the fracture methodology in actually trying to identify properties and combine this with various test specimen geometries, I think we have possibilities of coming about properties, mechanical properties of the interface. The way that

we're thinking about doing these measurements now is through a new digital imaging technique that allows you to do these things even through a scan electron microscope if you wish. I don't have time to go into the details. I'd better stop now.

Comment from Yoseph Bar-Cohen on Brinson's talk:
You talked about your ability but the kind of tests you did is mostly testing the elastic properties of the adhesive. What do you think of the use of sustained environmental loadings kind of tests where you load the structure and fix the level of stresses and look at the period where this structure is going to be maintaining that kind of load. Because just a peel test is not a good way of getting a measure, it's just yes or no.

Response from Brinson:
Well, sorry, I must not have made it clear. Both the 3-M durability test is done in an environmental cabinet so the specimens are loaded, put into the environmental cabinet and you just wait until they fail. In other words you measure the time to failure, so it's exactly what you mean and the same with the Boeing wedge test, the wedge is usually driven in with a hammer. It's a very imprecise test and then it's just dropped into an environmental cabinet and what they do is they measure the amount of crack propagation due to that environment. You can evaluate the effect of the environment as well as the surface treatment by trying to see whether the crack grows in cohesively or at the interface and there's reason for that to happen. What I'm suggesting is that a lot of people do this test in a qualitative way and we're suggesting that we should do it in a more quantitative way to get actual numbers out of it and that we should do it not only for mode one but for mode two as well and combinations thereof. You measure the length of the crack and the time it took to get there and you can actually calculate the fracture properties out of that.

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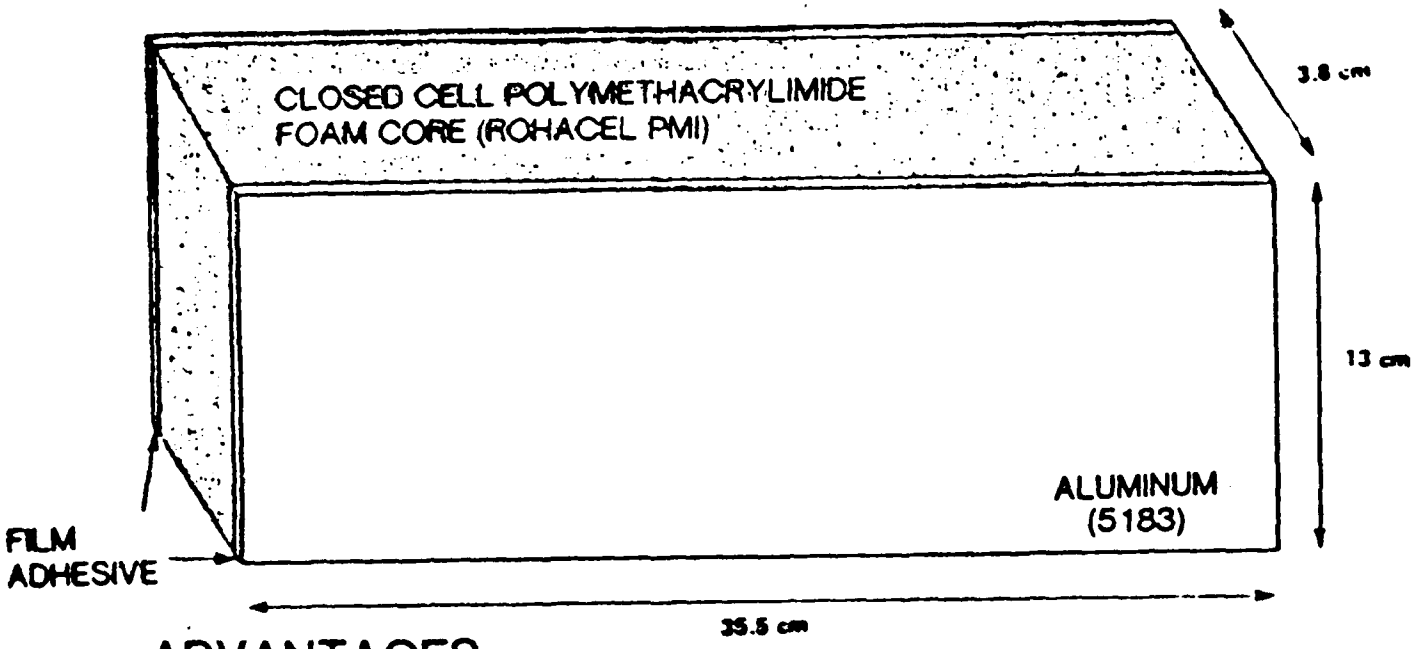
ASSESSMENT OF NDE TECHNIQUES FOR FOAM CORE/ALUMINIUM SANDWICH PANELS

The topic of my presentation is assessment of NDE techniques for foam core aluminum sandwich panels. This work was carried out at the Structures and Materials Laboratory of the National Aeronautical Establishment of NRC Ottawa, Ontario. The foam core panels were fabricated by Kingston Research Laboratory of Alcan International. Foam core aluminum panels are finding more applications in both aircraft and ground transport vehicles where safety plays an important role. These materials are fabricated by using a closed foam sandwiched between two aluminum plates using a layer of adhesive. The panel is then assembled and vacuum-bagged and cured for about an hour at high temperature. This (Figure 1) is the type of foam core we used in our evaluation and the size of the specimens used. These materials offer unique advantages over sheet metals. Some of the advantages are listed here: their high stiffness-to-weight ratio and their uniform load distribution and high bending and buckling resistance properties are utilized in structural applications. These properties along with their heat insulation and noise absorption are used in transport vehicles. However they have limitations too. They are susceptible to impact and fatigue damage and they're difficult to inspect by NDE methods.

Two examples of application of these materials are shown in this slide (Figure 2). The first one is a fuel cell support structure of the UH60 helicopter. In this application, the uniform load distribution property of the foam is utilized to distribute the weight of the fuel to the composite support structure. In the second application, which is a prototype of a rail car made by Oregon Transport Development Corporation in conjunction with Alcan, the side panels and roof are made of this foam core material. Here again, the stiffness and high noise and heat insulation properties are utilized. Alcan was interested in NDE methods both for control and verification of the fabrication processes as well as for flaw detection. So we were asked to carry out an assessment of NDE methods for these materials.

FOAM CORE ALUMINUM SANDWICH PANELS



ADVANTAGES

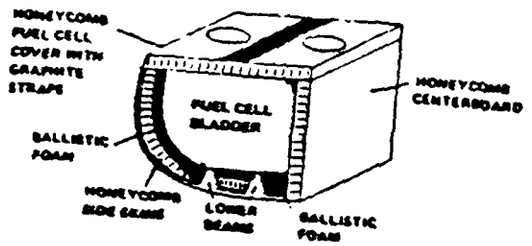
- HIGH STIFFNESS-TO-WEIGHT RATIO
- GOOD HEAT INSULATION
- UNIFORM LOAD DISTRIBUTION
- NOISE ABSORPTION
- HIGH BENDING AND BUCKLING RESISTANCE

LIMITATIONS

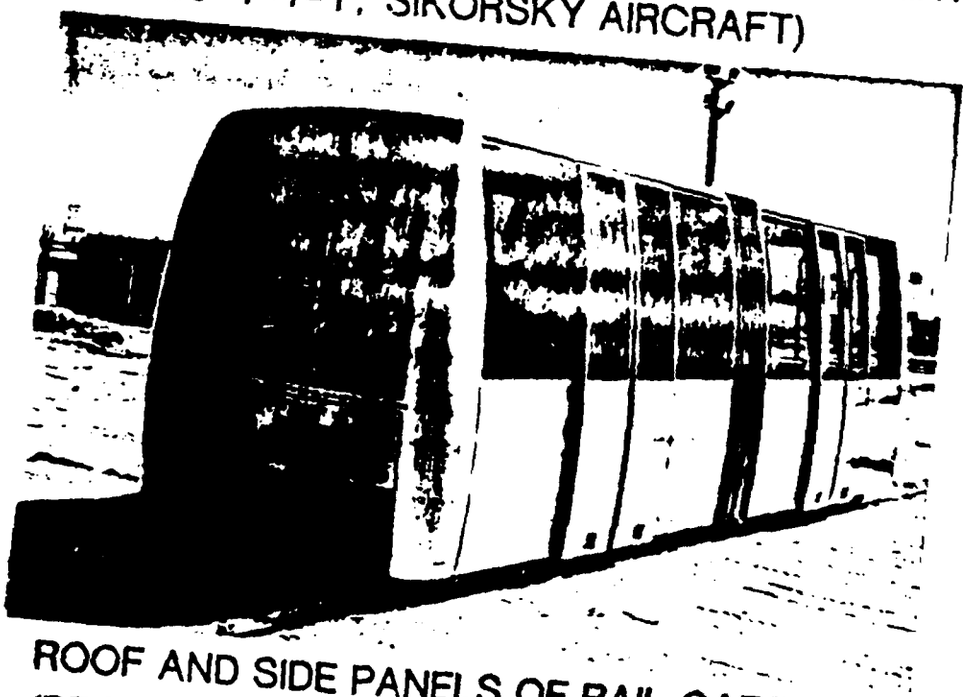
- SUSCEPTIBLE TO IMPACT AND FATIGUE
- DIFFICULT TO INSPECT BY NDE METHODS

FIGURE 1

EXAMPLES OF APPLICATIONS



FUEL CELL SUPPORT STRUCTURE OF UH-60 HELICOPTER (FROM: BRUCE PARKS, REPRINT NO 85-1-1-1, SIKORSKY AIRCRAFT)



ROOF AND SIDE PANELS OF RAIL CARS (PROTOTYPE MADE BY URBAN TRANSPORT DEVELOPMENT CORP. IN CONJUNCTION WITH ALCAN INTERNATIONAL)

FIGURE 2

For this assessment two groups of samples were evaluated. The first group contained defects and the second group were samples which were fabricated using different procedures. The first group contained artificial defects such as Teflon beds which were embedded between the aluminum face and the foam core and also unbond areas or voids which were introduced by cutting away part of the adhesive film. Also, some of the specimens were subjected to fatigue using two point bending configuration and the others were subjected to impact damage at different energy levels from one foot pound all the way to ten foot pounds. All these defects were invisible at the surface except the 10 foot pound impact damage which produced a visible dent on aluminum face.

The samples were then tested by a number of NDT methods which we had available in our laboratory (Figure 3). The choice of NDT techniques was based on their possible application to the foam core panels based on our experience with honeycomb sandwich panels which are very similar to these materials in terms of NDT application. The techniques included ultrasonic technique, conventional true transmission, pulse echo, backscattering and leaky Lamb wave methods. Also we looked at acousto-ultrasonic technique and mechanical impedance analysis and thermography which is still going on at Alcan. These methods were assessed in terms of their sensitivity, repeatability of detection of flaws, and their simplicity of application. The techniques employed, as you can see, cover a range of frequencies all the way from 1 kHz to 25 MHz.

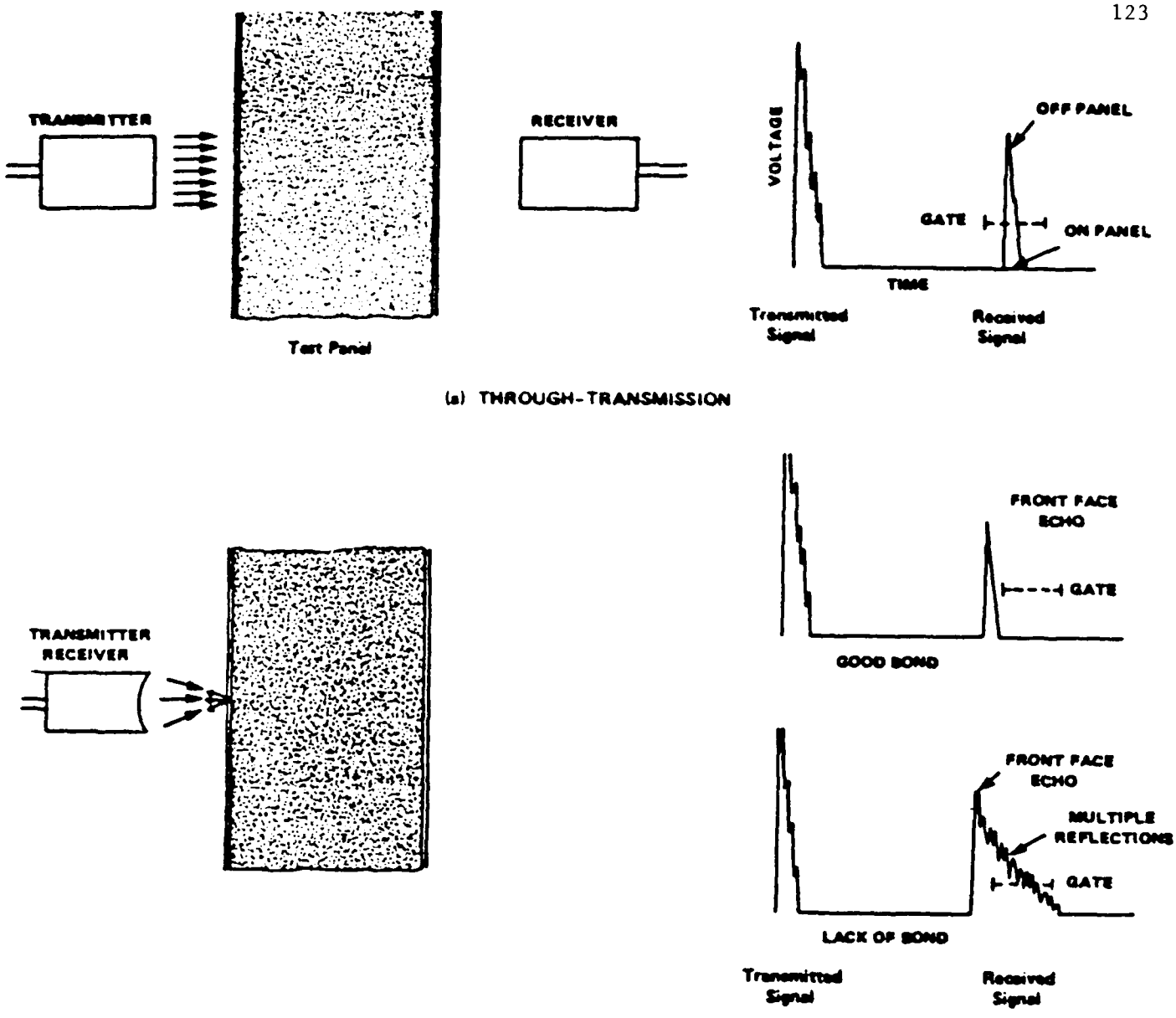
This (Figure 4) is the true transmission technique. The true transmission and pulse echo methods were used mainly as a comparison, as a basic technique to compare with the other newer methods like acousto-ultrasonics. In the true transmission which is shown here, we used our lowest frequency transducer that we had available which was a 500 kHz transducer and we used 500 volts, the highest possible that we could achieve in order to penetrate into the material. The thickness of the foam was about 1 inch. Still we were not able to penetrate into the foam so the true transmission didn't pick up any of the flaws.

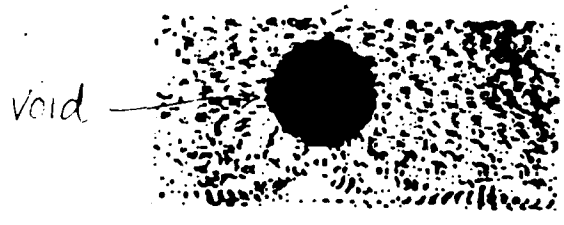
The pulse echo technique shown here carried out using 25 MHz transducer which we found was the optimum for this method. Since aluminum face sheet was only 0.040 inch thick multiple deflections occurred in the aluminum sheet which are shown here when there was a gap between the aluminum and the foam. However

NDE METHODS USED FOR FLAW DETECTION IN FOAM CORE PANELS

- ULTRASONICS (0.5–25 MHz)
  - THRU-TRANSMISSION USING 0.5 MHz PROBES
  - PULSE-ECHO USING 10–25 MHz PROBES
  - BACKSCATTERING USING 5 MHz PROBES
  - LEAKY LAMB WAVES USING 5 MHZ PROBES
- ACOUSTO-ULTRASONICS (0.15–3 MHz)
  - PITCH-CATCH USING DRY COUPLING WHEELED PROBES
- MECHANICAL IMPEDANCE ANALYSIS (1–8 kHz)
- THERMOGRAPHY (IN PROGRESS AT ALCAN)

FIGURE 3





THE THROUGH-TRANSMISSION & THE PULSE-ECHO METHODS & THE RESULTING C-SCAN PLOT

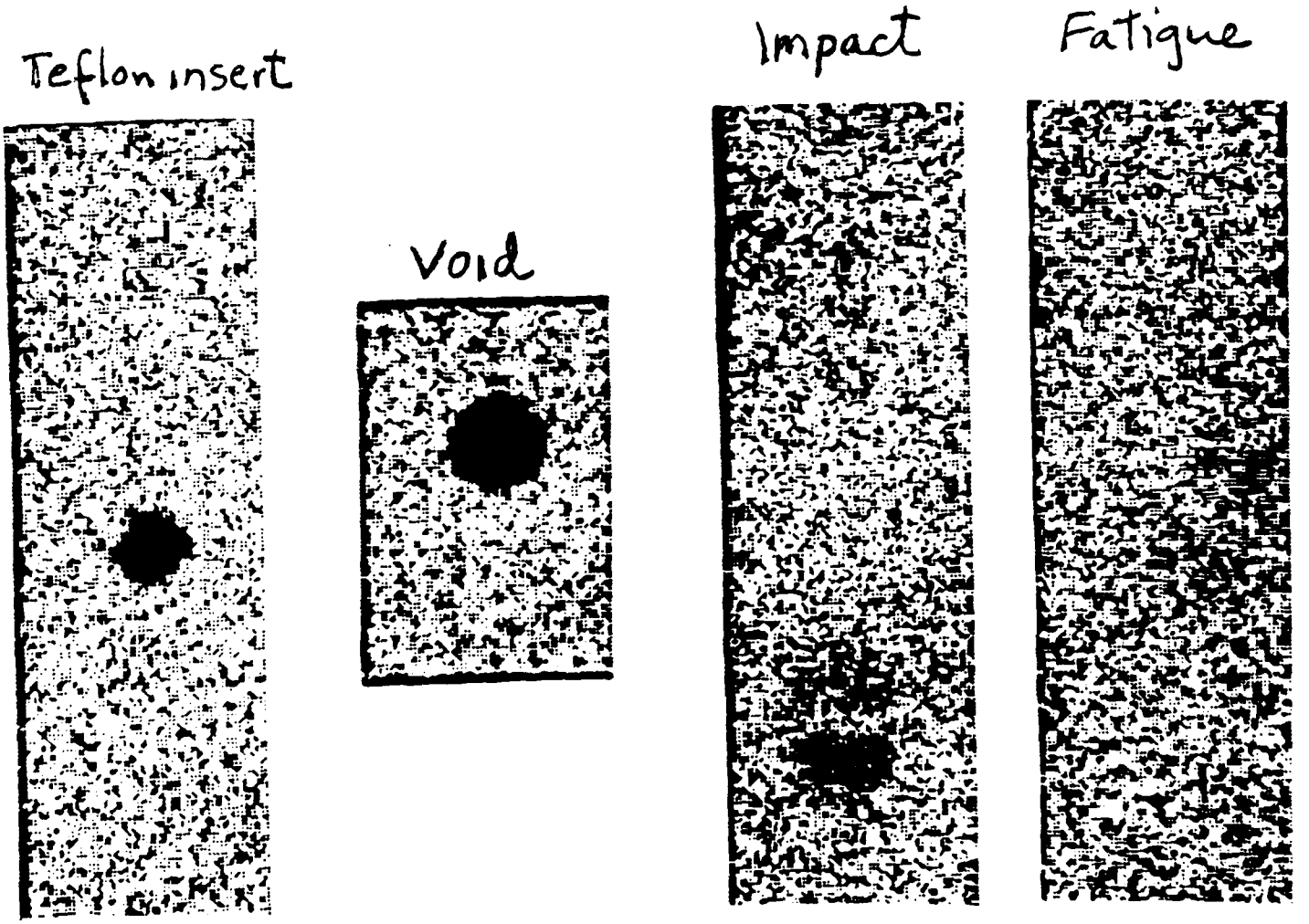
FIGURE 4

when there was no physical gap between aluminum and the foam there was only one signal, the signal was damped. So we put the gate on this ringing portion of the signal and carried out C-scan inspection using the pulse echo and this is what we got from the panel which contained physical gap or void or missing adhesive between the aluminum face and the core but the technique failed to detect fatigue and impact damages mainly because the fatigue and impact damage created the disbond between the adhesive and the core and the surface of this bond was rough. So there wasn't much energy reflected.

The next technique we tried was the backscattering method using a 5 MHz probe shown in Figure 5. For the same reason just mentioned for the pulse echo technique, the backscattering picked up the missing adhesive or the void shown in this C-scan. It also picked up the Teflon tape but it failed to pick up the impact damage or the fatigue damage. This indication here is the 10 foot pound impact which produced a visible dent on the aluminum face.

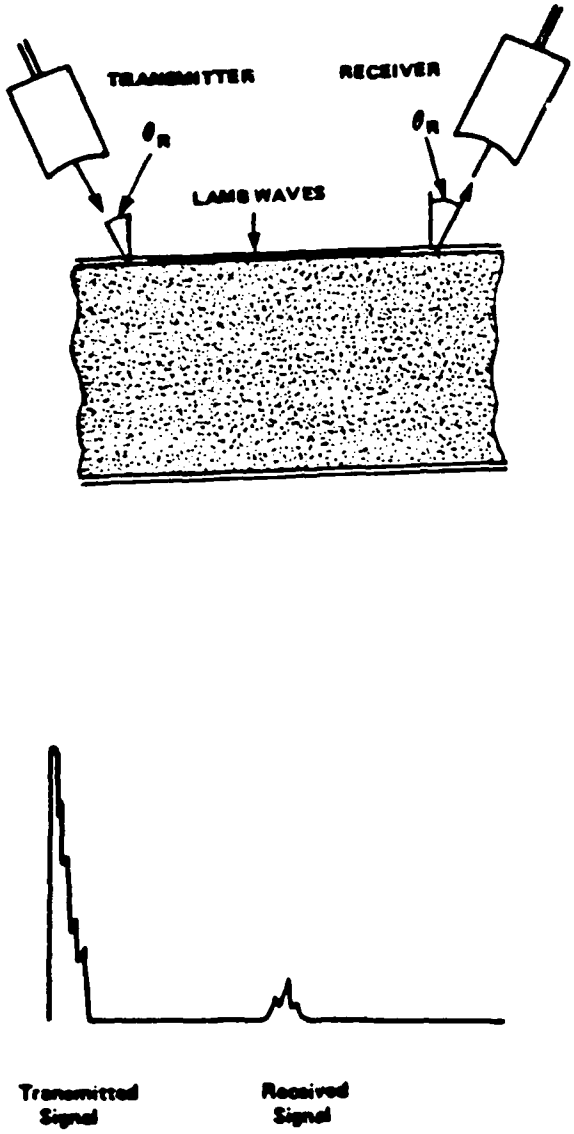
The next technique was the leaky Lamb wave method which is shown schematically here in Figure 6. We used two 5 MHz transducers which were placed some distance away and at an oblique angle with respect to the test material. It was thought that the propagation of the Lamb waves along the aluminum would be affected by the condition of the aluminum foam interface. However when we tried the technique experimentally, no flaws were detected regardless of the type of flaws.

Another method that we investigated was the mechanical impedance analysis (Figure 7). This technique measures the local impedance or the local response of a structure to a harmonic force and is defined by this equation where Z is mechanical impedance, F is the harmonic force, and v is the local velocity of the material or displacement, t is time, w is angular velocity, and ϕ is the phase angle. The mechanical impedance is also related by this equation to the mass of the material, the damping characteristics, and the local stiffness of the structure. So changes in the local stiffness due to the flaws would affect the mechanical impedance of the material which this instrument can measure. When the mechanical impedance was tried on the specimens, it picked up both fatigue and impact damages, and this (Figure 8) is the C-scan plot of the fatigue damage in one of the panels, but it failed to detect the small physical gap or the void and the Teflon tape mainly because the change in the stiffness was not sufficient for the instrument to pick up.



THE BACKSCATTERING METHOD AND THE RESULTING C-SCAN PLOTS

FIGURE 5



THE LEAKY LAMB WAVE TEST CONFIGURATION

FIGURE 6

MECHANICAL IMPEDANCE ANALYSIS (MIA)

MEASURES THE LOCAL IMPEDANCE (RESPONSE) OF A STRUCTURE TO A HARMONIC FORCE AND IS DEFINED BY :

$$Z = F/v$$

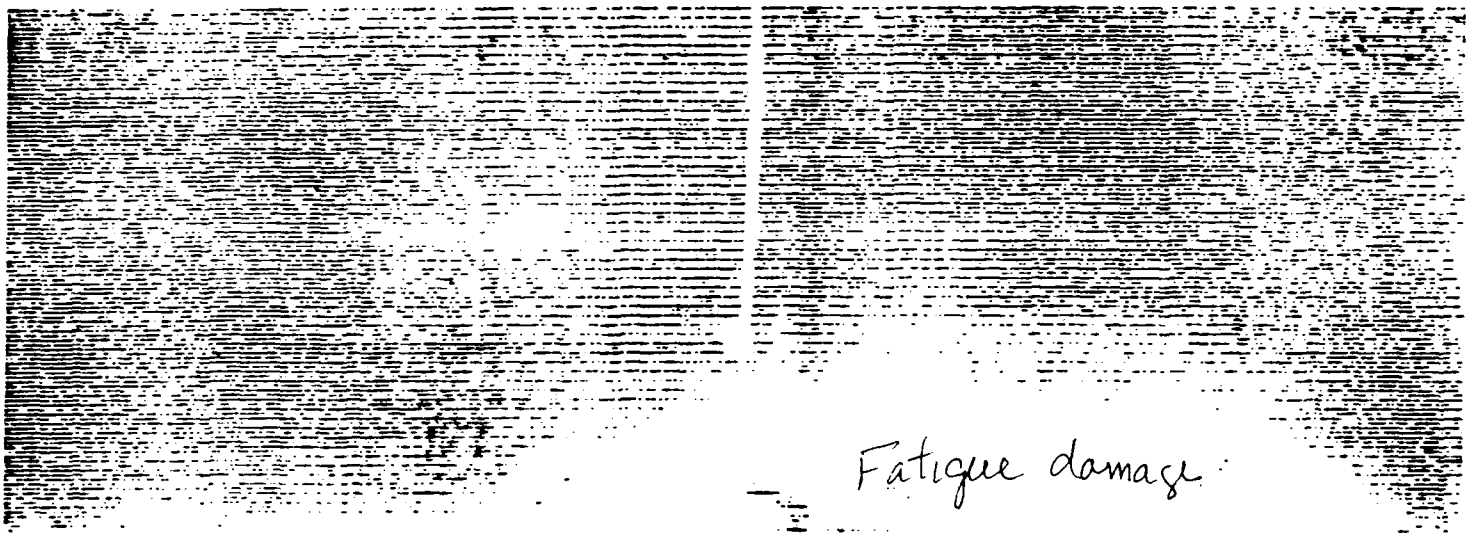
WHERE Z = MECHANICAL IMPEDANCE
F = HARMONIC FORCE = $F_o\ e^{(jwt-\phi)}$
v = RESULTANT VELOCITY AT THE POINT OF APPLICATION OF F
t = TIME
w = ANGULAR VELOCITY
ϕ = PHASE ANGLE

MECHANICAL IMPEDANCE IS GIVEN BY :

$$Z = R + j(wM - K/w)$$

WHERE M = MASS
R = DAMPING
K = LOCAL STIFFNESS

FIGURE 7



C-SCAN PLOT OF FATIGUE DAMAGE OBTAINED BY MIA

FIGURE 8

The next method we tried was the acousto-ultrasonic technique. In the acousto-ultrasonic technique, which is schematically shown in Figure 9, a repetitive ultrasonic signal is transmitted through a probe into the material and another probe receives the stress waves generated by the first probe. The second probe or the receiving probe is a more sensitive acoustic emission transducer and then the signals are analyzed in a similar fashion to acoustic emission. The operating frequency of the acousto-ultrasonic technique range from 150 kHz up to about 1 or 2 MHz. We used around 200 kHz in this experiment. The acousto-ultrasonic signals are characterized in different ways. For flaw detection in this experiment, we used AT206 bond tester which uses RMS of amplitude and uses dry coupling wheel probes as shown in this figure. The probes were manually scanned over the test specimens and the RMS values were taken and then later plotted as the function of the location of the probe. Here, in Figure 10, is the result for the specimen containing fatigue damage. This is the RMS value and there is where the fatigue damage is located. Notice there is this small change here, I will mention that later on. These are similar results obtained by acousto-ultrasonic technique for the specimen containing impact damage (Figure 11) . The RMS values as you could see increase with the extent of the damage produced by higher energy levels so there is a good relationship between the RMS value of the acousto-ultrasonic signal and the size of the damage.

After the NDT tests, several small holes were drilled on the aluminum face and liquid dye penetrant was injected through those holes into the foam to trace the defective areas. Then the aluminum face was peeled off and this is what the liquid penetrant test results indicated (Figure 13). This is the fatigued area. This is the impact damaged area. The size of the damage correlate well with the energy level and this is where that small change in the acousto-ultrasonic RMS value took place which is a poor bond between the foam and the aluminum. This choice is very closely matched with the results of the acousto-ultrasonic and to some extent with the results of the mechanical impedance analysis.

So let me at this stage conclude the results of the assessment of NDT techniques for the foam core (see Figure 14).

The ultrasonic technique using either normal pulse echo or backscattering method was found to be effective in detecting gaps, voids in the adhesive layer but ineffective in detecting impact or fatigue damage.

ACOUSTO-ULTRASONIC (AU) TECHNIQUE

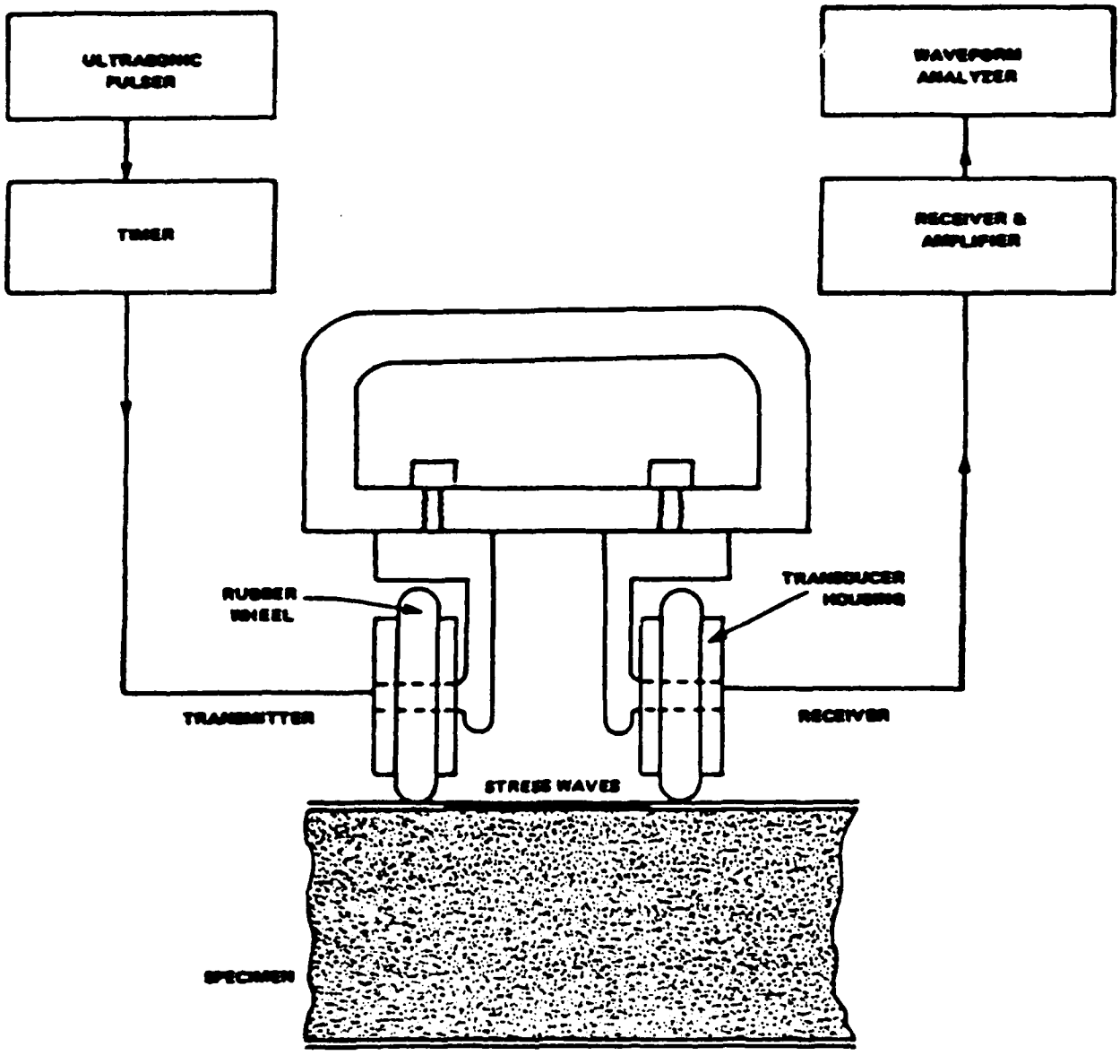
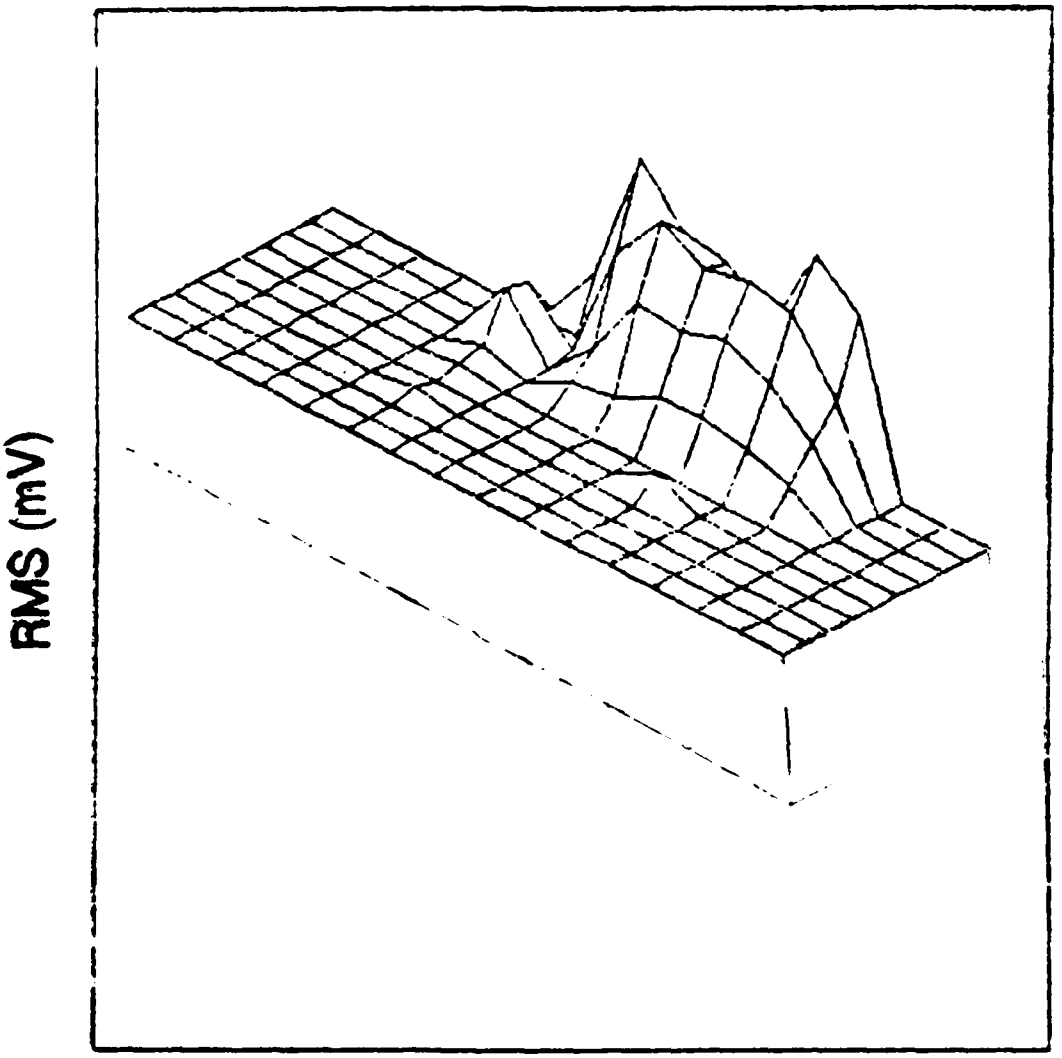
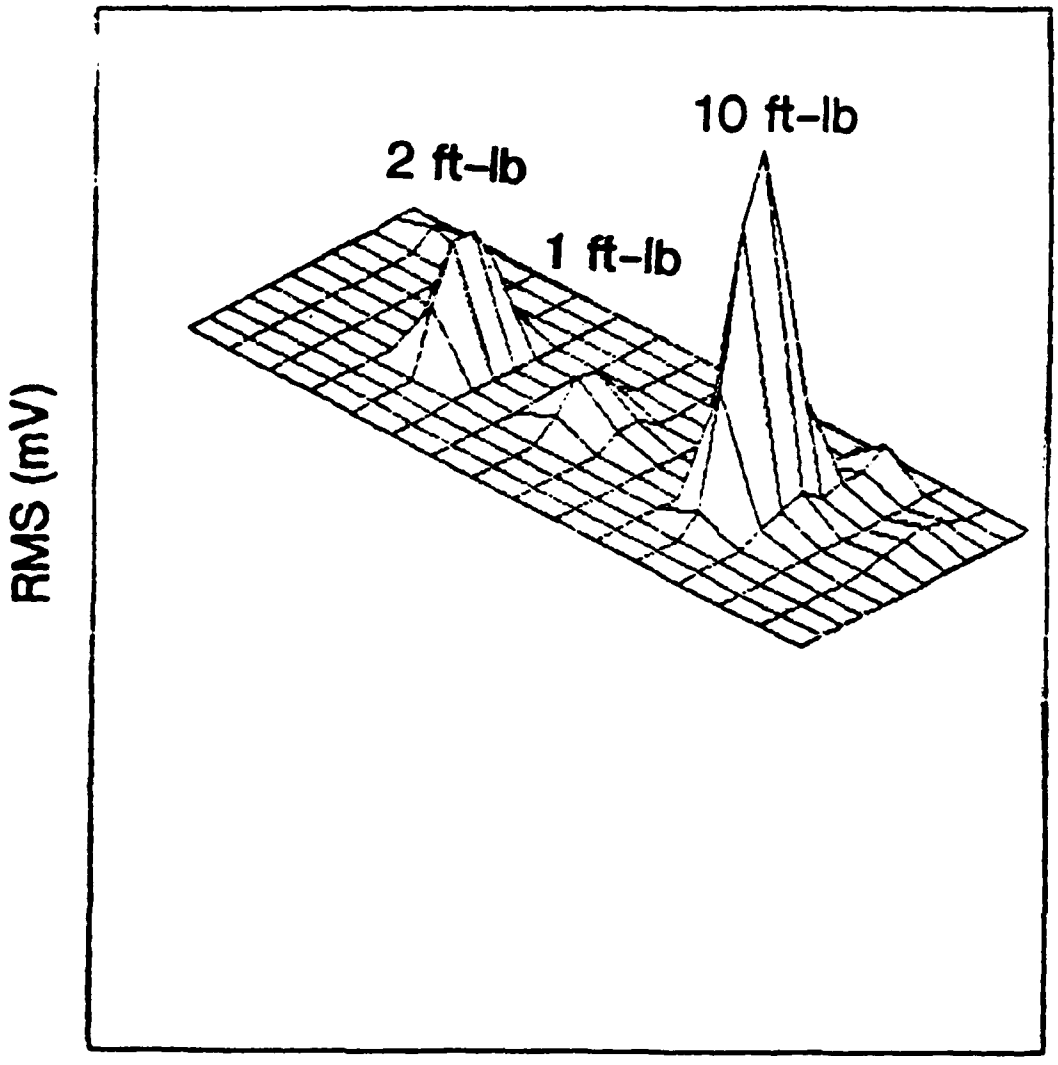


FIGURE 9



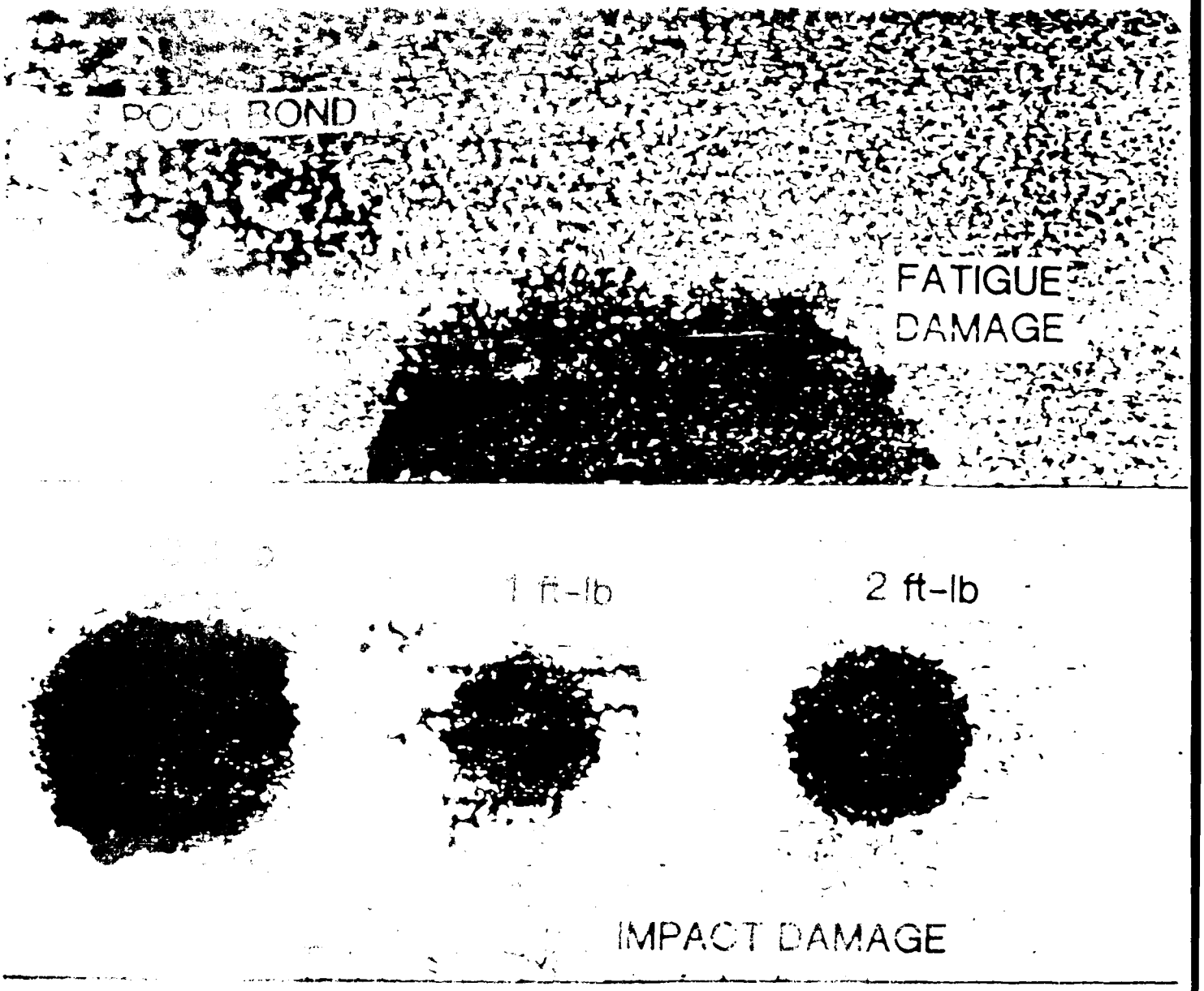
THE ACOUSTO-ULTRASONIC TEST RESULTS FOR THE PANEL CONTAINING FATIGUE DAMAGE

FIGURE 10



THE ACOUSTO-ULTRASONIC TEST RESULTS FOR THE PANEL CONTAINING IMPACT DAMAGE

FIGURE 11



PENETRANT TEST RESULTS FOR FOAM
LUMINUM PANELS CONTAINING
UE AND IMPACT DAMAGE. ALUMINUM
AS BEEN PEELED OFF.

CONCLUSIONS ON THE ASSESSMENT OF NDE TECHNIQUES FOR FOAM CORE ALUMINIUM PANELS CONTAINING DEFECTS (GROUP 1)

- THE ULTRASONIC TECHNIQUES USING EITHER NORMAL PULSE ECHO OR BACKSCATTERING METHODS WERE FOUND TO BE EFFECTIVE IN DETECTING GAPS IN THE ADHESIVE LAYER, BUT INEFFECTIVE IN DETECTING IMPACT OR FATIGUE DAMAGE

- MECHANICAL IMPEDANCE ANALYSIS, USING A CONTACT PROBE WITHOUT COUPLING FLUID, WAS SENSITIVE TO BOTH IMPACT AND FATIGUE DAMAGE, BUT INSENSITIVE TO A 25 mm DIAMETER GAP IN THE ADHESIVE LAYER

- THE ACOUSTO-ULTRASONIC METHOD, USING A DRY COUPLING WHEELED PROBE, WAS SENSITIVE TO ALL DEFECTS PRESENT IN THE PANELS AND PROVIDED INFORMATION RELATED TO THE SEVERITY OF FLAWS

FIGURE 14

Mechanical impedance analysis using a contact probe without coupling was sensitive to both impact and fatigue damage but insensitive to a small gap in the adhesive layer.

The acousto-ultrasonic method using a dry coupling wheel probe was sensitive to all the defects we looked at. It also gave some information about the severity of the flaws.

Based on the results of these assessments, we decided to use the acousto-ultrasonic technique and the mechanical impedance analysis to evaluate variation in the fabrication processes. For this purpose we looked at the second group of specimens which were fabricated using different fabrication processes (Figure 15). These processes resulted in different surface textures between the foam and the adhesive. In some specimens a primer was used and each group contained control specimens and specimens which I designate by surface finish A, B, and some of them use two layers of adhesive. Each of these produce different mechanical strength characteristics. These panels first tested by acousto-ultrasonic and then mechanical impedance analysis nondestructively, after that they were destructively tested using kline drum peel test to verify and to get correlation with NDT results. Figure 16 is the flow chart for the NDE and destructive tests. The acousto-ultrasonic measurements were taken in six locations and the same for mechanical impedance analysis. This is the ASTM standard method (ASTM D1781) used for obtaining the peel strength results (Figure 17). This is the standard method for sandwich panels, here is the specimen and the specimen is held both sides and the rotating drum is there to peel off the face.

For acousto-ultrasonic measurement first we tried the rubber wheel probes using the AET206 instrument which I mentioned earlier and took the RMS data. But we found out that it was not as sensitive to fabrication changes as it was to the defects. Then we used a more elaborate setup which is shown here in Figure 18 which consisted of SAT pulser and a repetition counter and controller, an AET500 transmitting transducer and here is an AET375 receiving transducer and AET5000 acoustic emission instruments and the Data 6000 for digitization and signal processing. This (Figure 18) is just a picture of the instrumentation, AET5000 here is Data 6000 there and this is the jig on which the transducers were put and

GROUP 2 SAMPLES

FABRICATED USING VARIOUS PROCEDURES

- WITHOUT PRIMER
  - Controls
  - Surface Finish A
  - Surface Finish B, One Adhesive Layer
  - Surface Finish B, Two Adhesive Layers
- WITH PRIMER
  - Controls
  - Surface Finish A
  - Surface Finish B, One Adhesive Layer
  - Surface Finish B, Two Adhesive Layers

FIGURE 15

NDE & DESTRUCTIVE TESTS FOR FOAM CORE PANELS MADE BY USING VARIOUS FABRICATION PROCEDURES

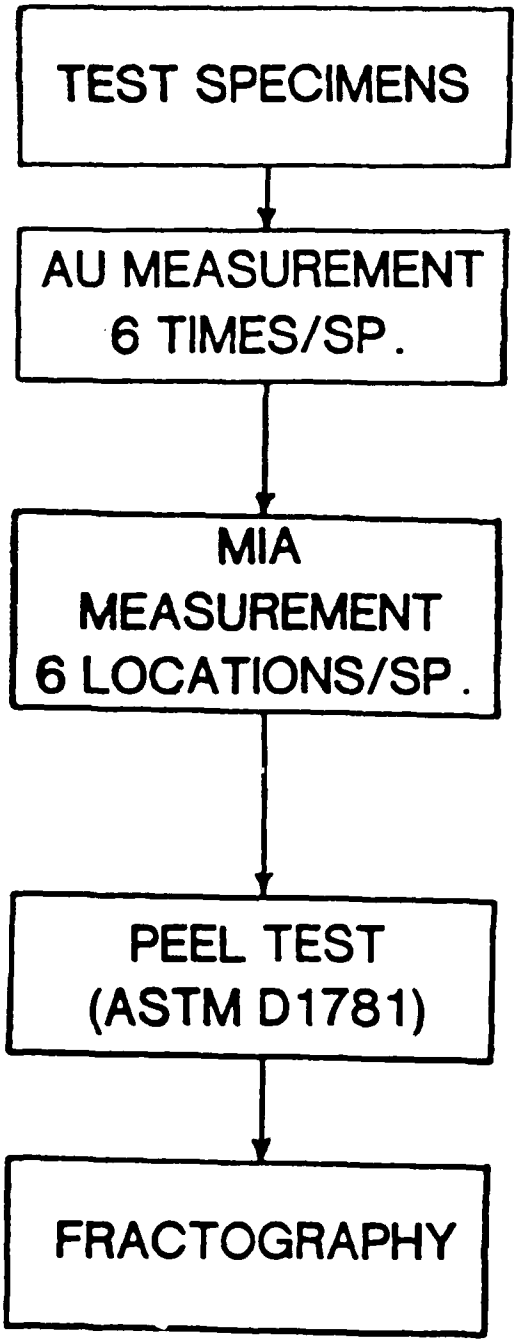


FIGURE 16

ASTM STANDARD METHOD FOR THE CLIMBING DRUM PEEL TEST FOR SANDWICH PANELS (ASTM D1781)

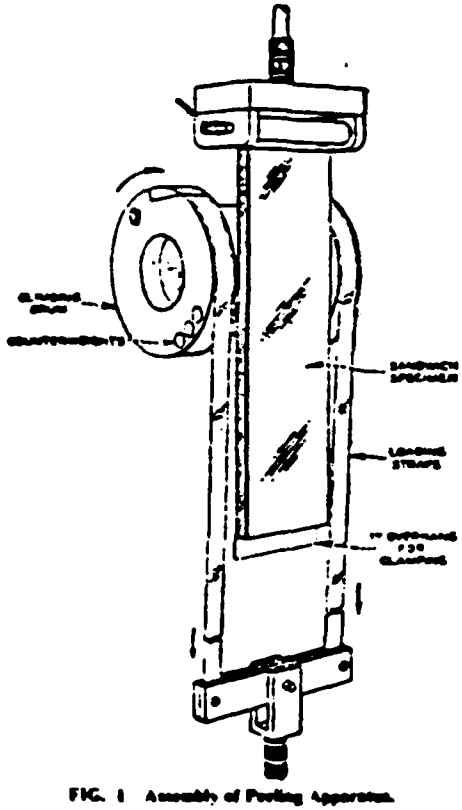


FIG. 1 Assembly of Peeling Apparatus

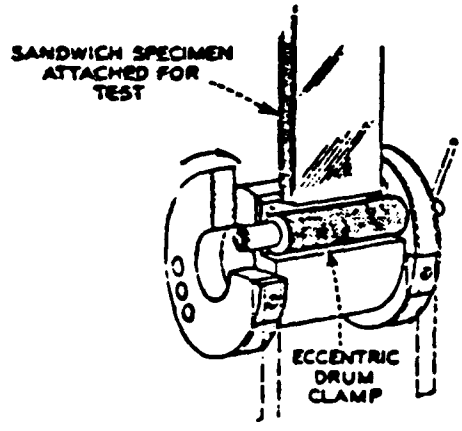


FIG. 2 Drum Clamp

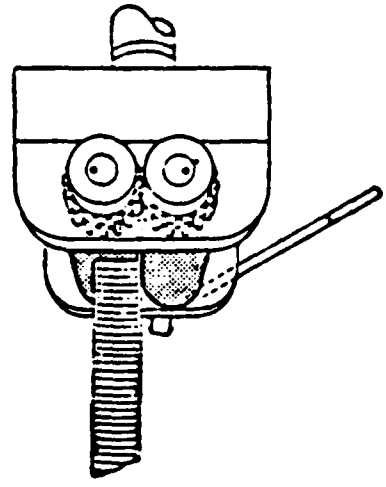
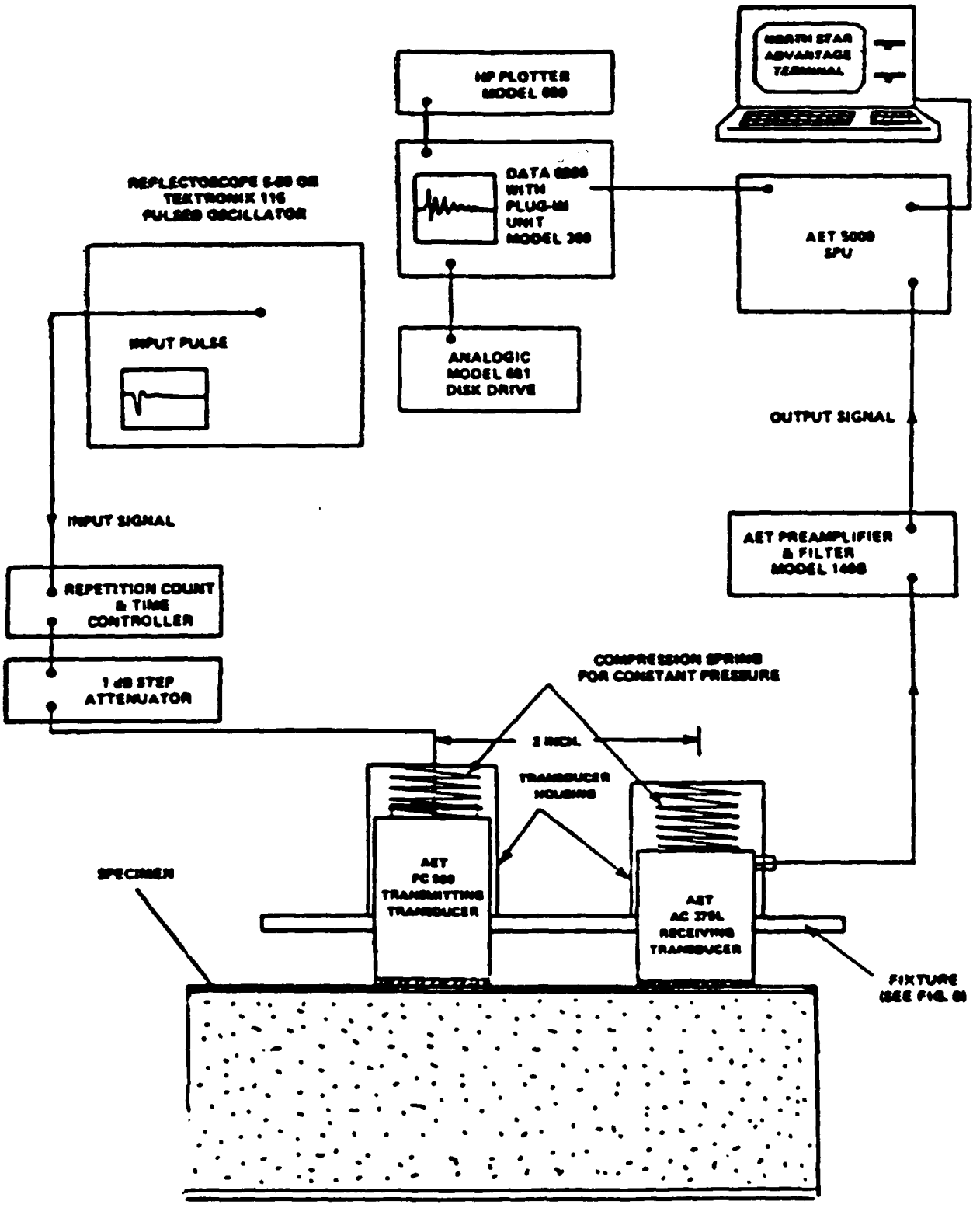


FIG. 3 Top Clamp

FIGURE 17



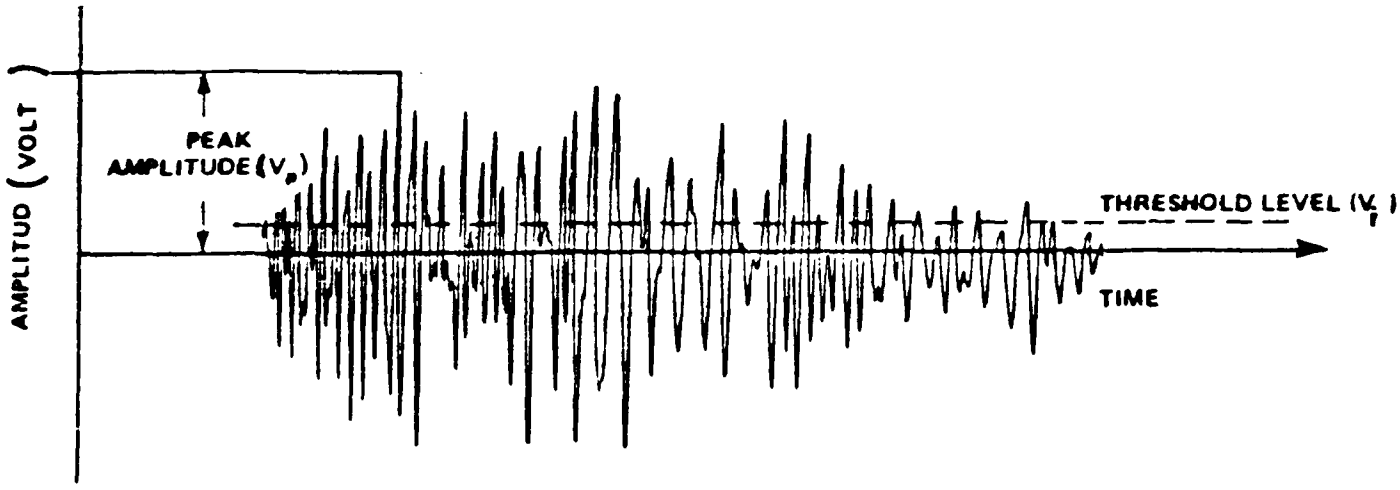
A SCHEMATIC OF THE ACOUSTO-ULTRASONIC SYSTEM USED IN THIS INVESTIGATION

FIGURE 18

spring loaded onto the specimen in order to increase the repeatability of the measurements. These are two acousto-ultrasonic signals (Figure 19). This one is from a control specimen and this one is from another specimen with different surface textures. Obviously you see a significant change in the acousto-ultrasonic signal. The acousto-ultrasonic signals are characterized in different ways as I mentioned earlier.

Alex Vary who first invented the acousto-ultrasonic technique defined stress wave factor which is in fact multiplication of the ring down count exceeding a predetermined threshold level by the repetition rate of the signal and a predetermined time interval (Figure 20). The SWF obviously does not consider the amplitude of the signal. Later Williams and Lampert from MYT used a somewhat different parameter to measure the characteristics of the acousto-ultrasonic signal and they called it modified SWF which was in fact the summation of the amplitudes of the signal. Based on this we use this expression in Figure 20 to obtain the summation of the amplitudes. This is schematically shown in this diagram; basically we increase the threshold from zero all the way to the maximum amplitude in small increments and then add up the amplitude values in each increment until the whole signal is covered. We call that acousto-ultrasonic parameter and from now on I'll use AUP for that. Here in Figure 21 we see the AUP as a function of peel torque strengths for the foam core panels. As you can see the specimens which had the primer and those which had no primer formed separate, or almost separate groups, except this one here. There was a good correlation between the AUP and the peel strength of the material. These bars show the standard deviation.

Figure 22 shows the mechanical impedance results as a function of peel strength. Here the amplitudes are shown. Again the two groups were differentiated by the technique and there was some correlation in one of the groups but the other group really didn't show any correlation. These are the amplitude results of the mechanical impedance. Figure 23 shows the phase results of the mechanical impedance. Similar to the amplitude, the two groups could be differentiated and the first group showed some correlation but not the second one.


AMPLITUD (VOLT)
PEAK AMPLITUDE (V_p)
THRESHOLD LEVEL (V_t)
TIME

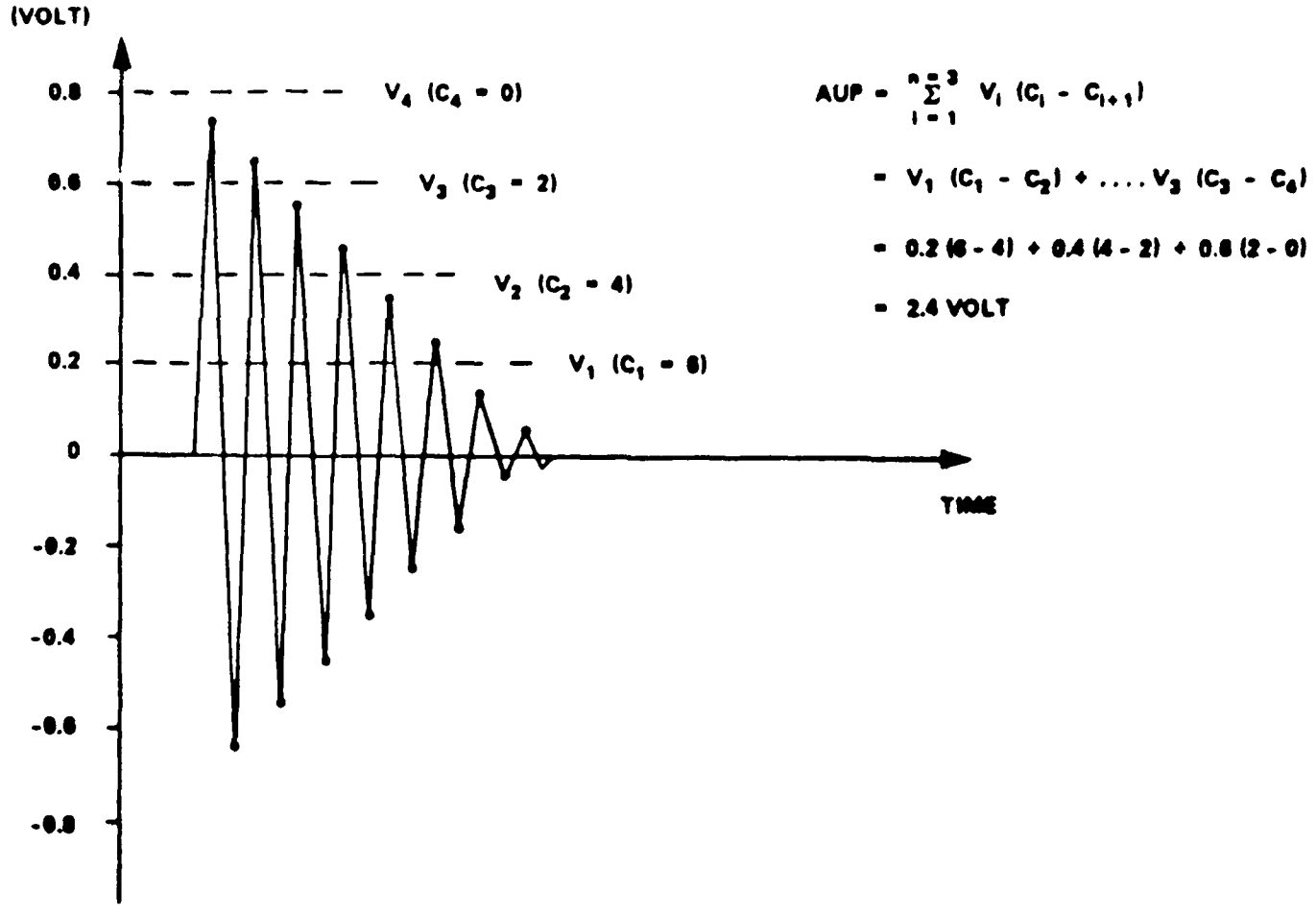

(VOLT)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
V_4 (C_4 = 0)
V_3 (C_3 = 2)
V_2 (C_2 = 4)
V_1 (C_1 = 6)
TIME
AUP = $\sum_{i=1}^{n=3} V_i (C_i - C_{i+1})$
= $V_1 (C_1 - C_2) + \ldots . V_3 (C_3 - C_4)$
= 0.2 (6 - 4) + 0.4 (4 - 2) + 0.8 (2 - 0)
= 2.4 VOLT

FIGURE 19

- ALEX VARY DEFINED THE STRESS WAVE FACTOR (SWF) AS :

$$SWF = R.T.C$$

R = REPETITION RATE OF INPUT WAVEFORM
T = A PREDETERMINED TIME INTERVAL
C = NUMBER OF OSCILLATIONS IN THE WAVEFORM EXCEEDING THRESHOLD

- WILLIAMS AND LAMPERT USED THE SUM OF AMPLITUDES

$$\text{MODIFIED SWF} = V_1 + V_2 \ldots\ldots V_n$$

- BASED ON THE ABOVE, THIS WORK USES ACOUSTO-ULTRASONIC PARAMETER (AUP) AS:

$$AUP = \sum_{i=0}^{p} V_i (C_i - C_{i+1})$$

V_i = THRESHOLD LEVEL
C = NUMBER OF COUNTS
i = 0 TO p

FIGURE 20

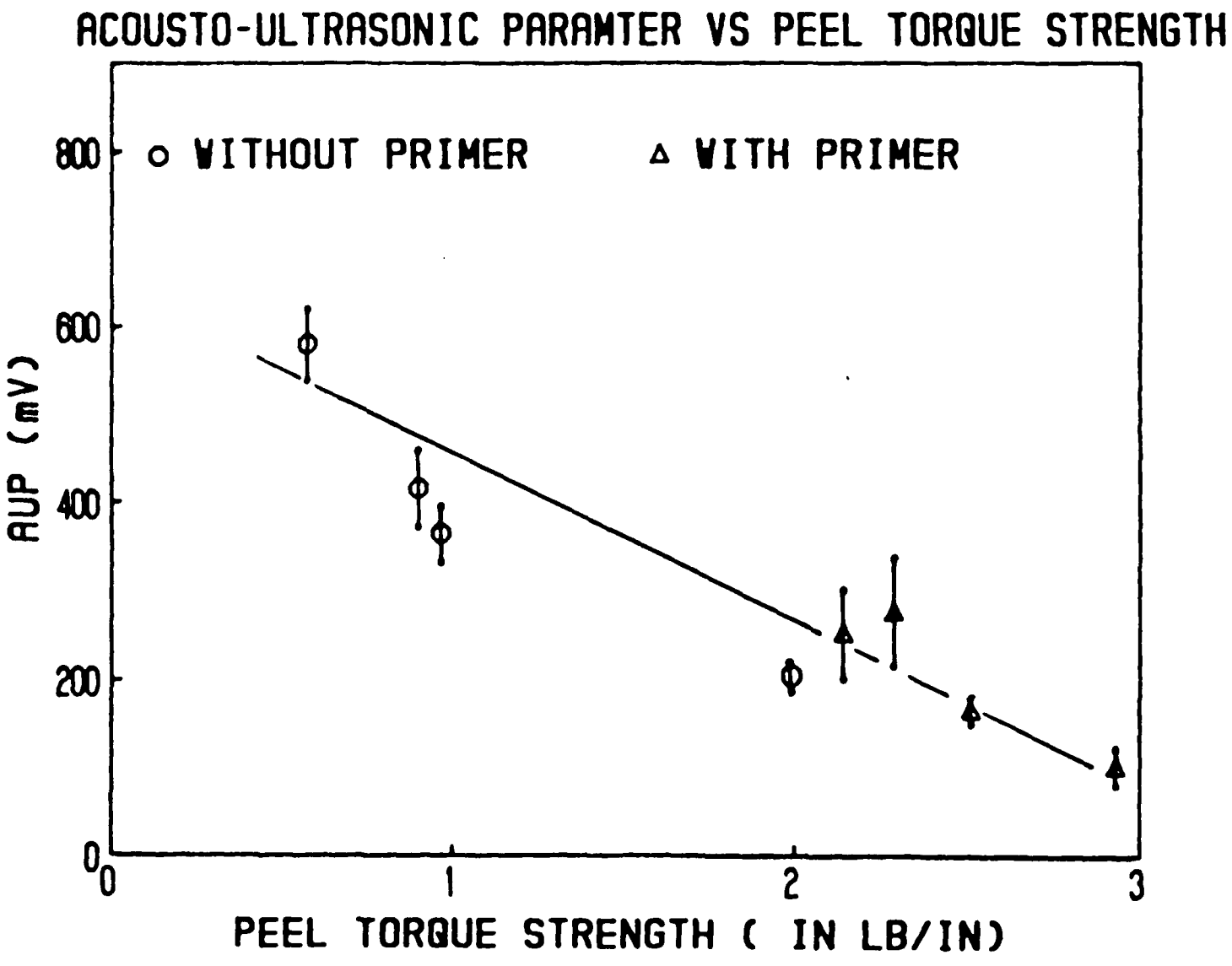

ACOUSTO-ULTRASONIC PARAMTER VS PEEL TORQUE STRENGTH
o WITHOUT PRIMER
Δ WITH PRIMER
AUP (mV)
800
600
400
200
0
0
1
2
3
PEEL TORQUE STRENGTH (IN LB/IN)

FIGURE 21

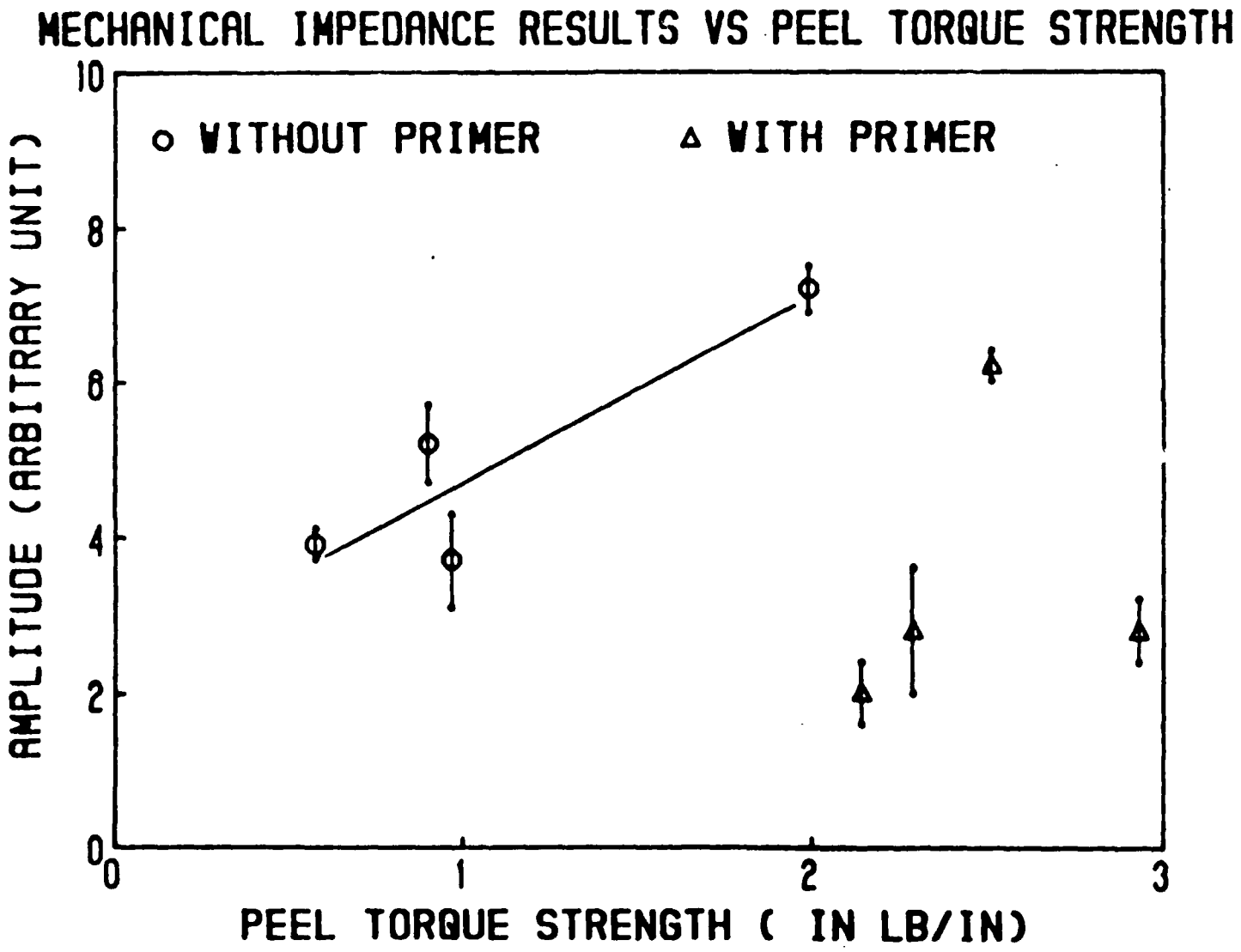

MECHANICAL IMPEDANCE RESULTS VS PEEL TORQUE STRENGTH
WITHOUT PRIMER
WITH PRIMER
AMPLITUDE (ARBITRARY UNIT)
PEEL TORQUE STRENGTH (IN LB/IN)
0
2
4
6
8
10
0
1
2
3

FIGURE 22

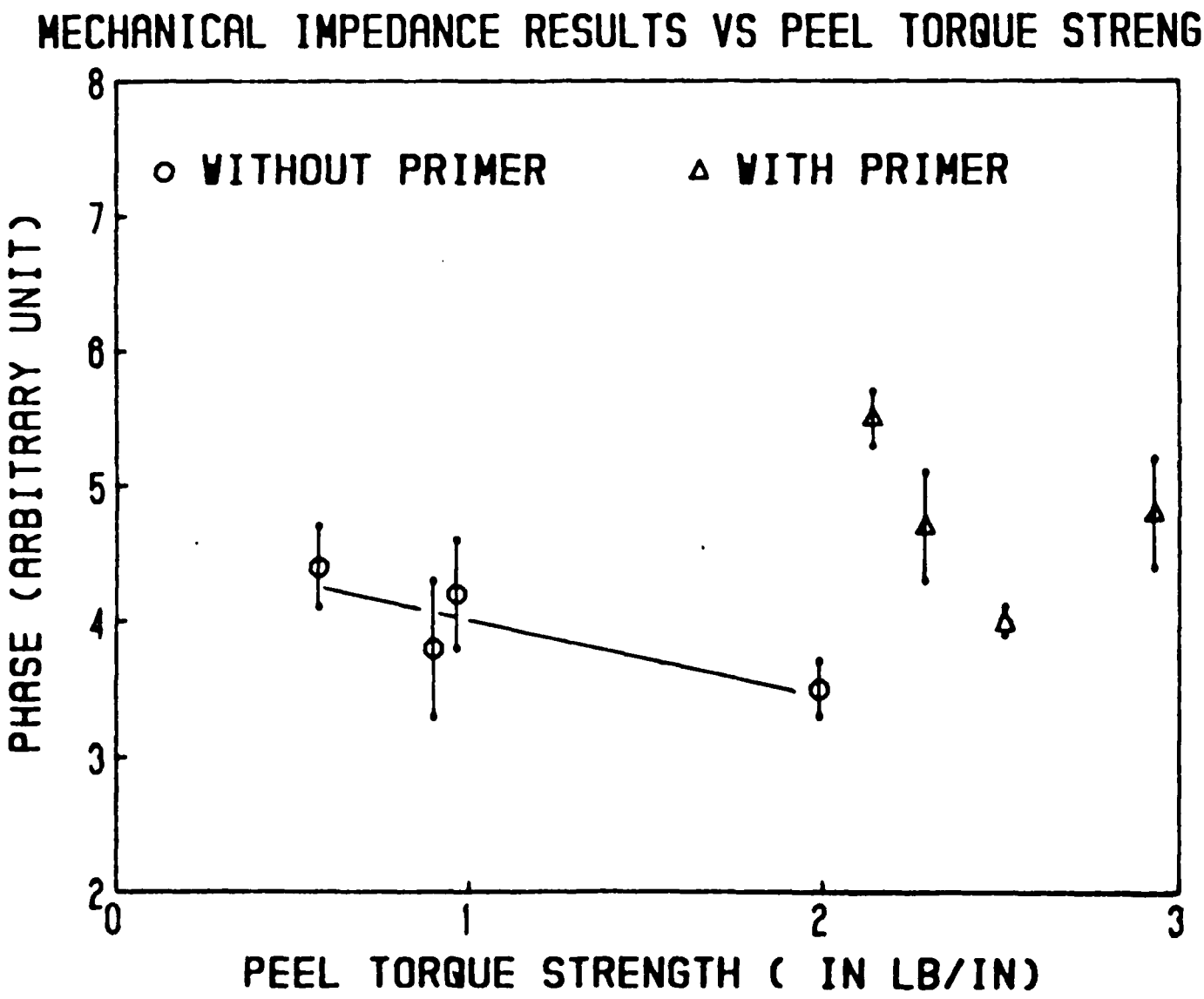
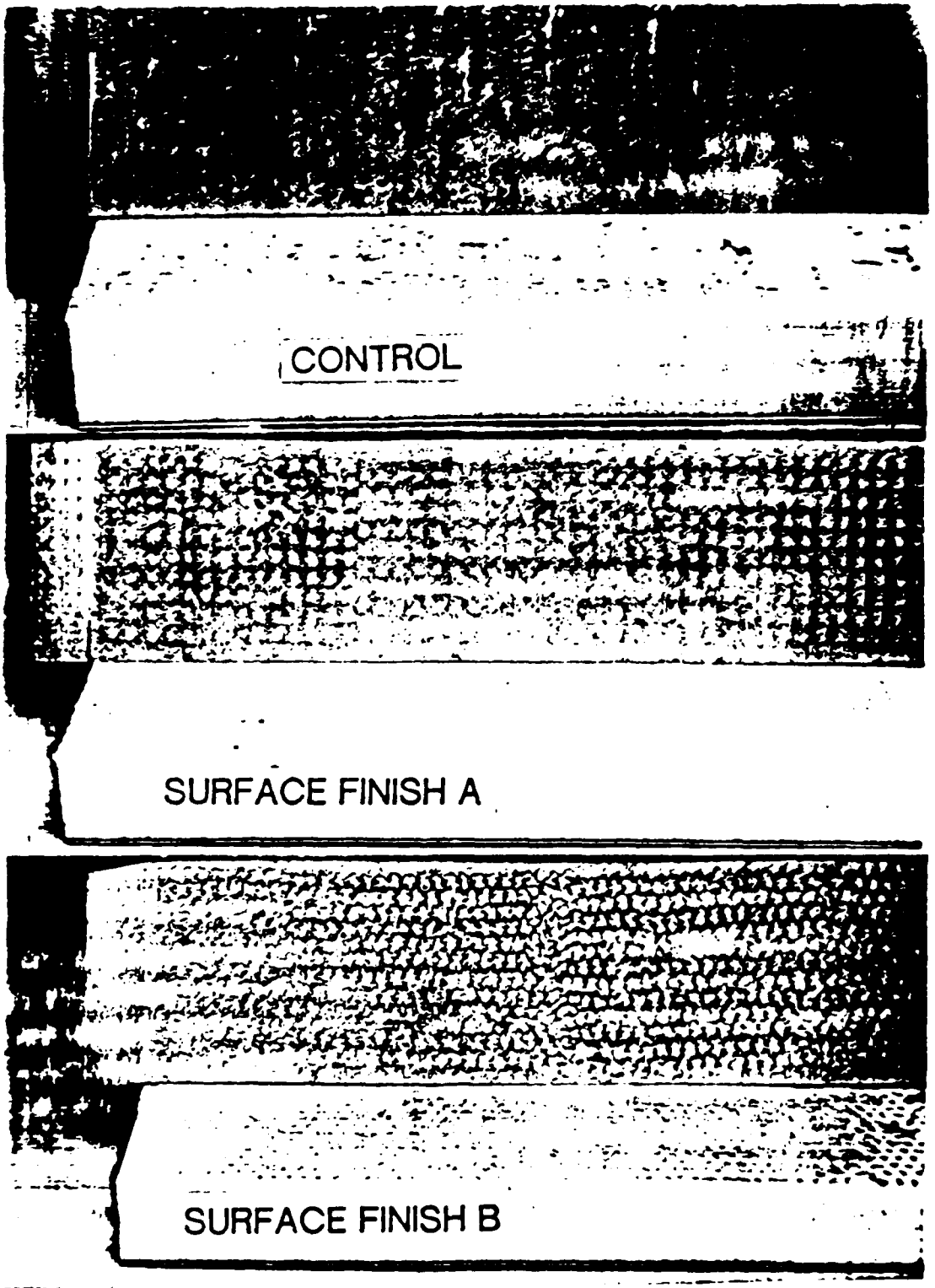

MECHANICAL IMPEDANCE RESULTS VS PEEL TORQUE STRENGTH
o WITHOUT PRIMER
Δ WITH PRIMER
PHASE (ARBITRARY UNIT)
8
7
6
5
4
3
2
0
1
2
3
PEEL TORQUE STRENGTH (IN LB/IN)

FIGURE 23

In Figure 24 are just some examples of the fracture surfaces of the foam core aluminum panels. This is the aluminum part and this is the foam in all cases. This is the controller specimen which failed at the interface between foam and the adhesive, primarily failed interfacially. The specimen which had a different texture than the control again failed between the adhesive and the foam but had the mixed mode, interfacial as well as cohesive failure. There was more cohesive failure in the third sample. These modes of failure produce different strength results as you saw in the previous slides.

So in conclusion, using the mechanical impedance method, it was possible to differentiate between specimens fabricated with and without primer but the sensitivity was not good. Some correlation was observed between the mechanical impedance analysis data and the peel torque strength for specimens fabricated without a primer. Using the acousto-ultrasonic method it was possible to differentiate between the specimens fabricated with and without primer with a much better sensitivity and a good correlation was found between the acousto-ultrasonic parameter and the peel torque strengths of all foam core panels. These correlations suggest that the acousto-ultrasonic method may be used to nondestructively monitor or assess the adhesive bond in the foam core panels (Figure 25). Thank you very much.



PHOTOGRAPHS OF FRACTURE SURFACES OF FOAM CORE ALUMINUM PANELS AFTER PEEL TORQUE TESTS

FIGURE 24

CONCLUSIONS ON THE ASSESSMENT OF NDE TECHNIQUES FOR FOAM CORE PANELS FABRICATED USING DIFFERENT PROCEDURES (GROUP 2)

- USING THE MIA METHOD, IT WAS POSSIBLE TO DIFFERENTIATE BETWEEN SPECIMENS FABRICATED WITH AND WITHOUT A PRIMER BUT THE SENSITIVITY WAS RELATIVELY POOR

- SOME CORRELATION WAS OBSERVED BETWEEN THE MIA DATA AND THE PEEL TORQUE STRENGTH FOR SPECIMENS FABRICATED WITHOUT A PRIMER

- USING THE AU METHOD, IT WAS POSSIBLE TO DIFFERENTIATE BETWEEN SPECIMENS FABRICATED WITH AND WITHOUT A PRIMER WITH SIGNIFICANTLY BETTER SENSITIVITY

- GOOD CORRELATION WAS FOUND BETWEEN THE ACOUSTO-ULTRASONIC PARAMTER AND THE PEEL TORQUE STRENGTH OF ALL FOAM CORE PANELS

- THE CORRELATION SUGGESTS THAT THE AU METHOD MAY BE USED TO NONDESTRUCTIVELY MONITOR OR ASSESS ADHESIVE BOND STRENGTH IN FOAM CORE ALUMINUM PANELS

FIGURE 25

Due to difficulties with the recording equipment, portions of the following presentation were not recorded. The author has furnished the following summary of his presentation.

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University of Illinois
Urbana, Illinois
Telephone: (217) 333-1228

ADHESIVE BOND STRENGTH QUALITY ASSURANCE USING THE STRESS WAVE FACTOR TECHNIQUE

This presentation addresses the use of the acousto-ultrasonic stress wave factor technique as a nondestructive evaluation/characterization of the adhesive bond strength between rubber layers and steel plates.

Adhesion, or strength of the bond between rubber and other material (metal, plastic, or other rubber), is a critical requirement for the functioning of a great variety of products which are vulcanized composites of two or more materials. Usually, adhesion is measured using the destructive stripping or peeling method, ASTM D429-81 (ASTM, 1985). The need for a nondestructive testing method to evaluate the strength of the adhesive bond between rubber and other materials has long been established.

Acousto-ultrasonic is a NDE technique which measures the relative efficiency of energy transmission in the specimen. An ultrasonic pulse is injected with a transmitting transducer mounted on the surface of the specimen. A larger amount of damage in the specimen produces a higher signal attenuation, resulting in lower Stress Wave Factor (SWF) readings. Traditionally, the SWF is evaluated as the number of oscillations higher than a chosen threshold in the ringdown oscillations in the output signal from the receiving transducer. The SWF has already been correlated with the mechanical strength of composite materials by Vary and Lark (1978), Williams and Lampert (1980), Kautz (1985), and Govada, et al. (1985). SWF measurements have also been correlated with the peel strength of copper cladding bonded to glass/polyimide used in printed circuit board production as reported by Rodgers (1983). A good review of analytical ultrasonics in materials research and testing is given in Vary, ed. (1984).

Traditioinally, the SWF readings depend upon several instrumentation and experimental parameters such as the threshold level. To eliminate this dependence, the signal energy has been used to define the SWF, Kautz (1985), where the signal energy is defined as the square of the

amplified transducer output voltage integrated over the time of the sweep. An alternate method for quantifying the SWF has been proposed by Govada et al (1985). This method consists in using a Fast Fourier Transform (FFT) to perform the spectral analysis of the output signal. It is based on the observation by Talreja (1973) that three classes of parameters are needed to describe distribution functions (power spectrum in particular), namely location, scale, and shape parameters. Talreja (1973) suggested that a convenient set of parameters to represent the frequency spectrum can be defined as follows: the location parameter can be taken to be the location of the centroid of the spectrum; the area of the spectrum forms a suitable scale parameter, and the shape parameters can be described in terms of the various moments of the power spectrum about a convenient axis. Following Govada et al. (1985), the root mean square of the power spectral density, $(M_0)^{1/2}$, is used as an alternate method to quanitfy the SWF.

Thirty-two specimens for peel strength testing were prepared, per ASTM D429-81 (ASTM, 1985). Each specimen consisted of a rubber sheet with a thickness of 6 mm (1/4 in.) and dimensions of 25 x 127 mm (1 x 5 in.) which was bonded in vlucanization process, when they were placed in the mold under high pressure and temperature. The test specimens were prepared such that the bonded area of 25 x 25 mm (1 x 1 in.) was located approximately in the middle of the metal member. Using a Shore A-2 durometer testing machine, the rubber had an average hardness of 51. The steel plate surface was grit blasted. The thirty-two specimens were divided into eight groups of four equal specimens each. To assure specimens with different quality of bond peel strength between the rubber and the steel plate, each group of four equal specimens was prepared with a different amount of adhesive (i.e., primer cement and cover cement) and with controlled defects in the bonded surface areas as described in Table 1. Three of the controlled defects were obtained by masking a portion of the bonded area prior to the application of the adhesive system. Four other defects were obtained by deleting either the primer cement or the cover cement in conjunction with contamination of the bond surface with a centrally located thumb print.

A schematic diagram of the Stress Wave Factor measurement system is shown in Fig. 1. The broad-band transmitting transducer was the AET Model FC-500 having approximately a flat sensitivity of -85 dB (relative to 1V/μ bar) from 0.1 to 3 MHz. The resonant receiving transducer was the AET Model AC-375L having an approximate sensitivity of -65 dB (relative to 1V/ μ bar) at the resonant frequency of 375 kHz. Both the transmitting and the receiving transducers were mounted in waveguides as shown in Fig. 1. The area of contact between each waveguide and the specimen was a circle with a diameter of 6.4 mm (1/4 in.). The center-to-center spacing between

the waveguides was 38 mm (1.5 in.), and the contact pressure between the waveguides and the specimen was such that the saturation pressure was exceeded.

The transmitting transducer was excited by an ultrasonic pulser (Parametric, Model 5052 PRX) which was set at the pulsing rate of 200 pulses/s. The output signal from the receiving transducer was amplified by 20 dB in a preamplifier (Dunegan/Endevco, Model 301). The acousto-ultrasonic signal waveform was then digitized in a digitizing oscilloscope (Tektronix, Model 7854) using 1024 points. The calculations for the signal energy and for the power spectrum analysis were then carried out by a Tektronix computer (Model 4052) equipped with a signal processing ROM.

For the peel strength tests, the load was applied at an angle of 45^{o} using a Scott tensile testing machine with a constant crosshead speed of 0.8 mm/s (2.0 in/min).

Figure 2 shows a full frequency range acousto-ultrasonic signal in the time domain together with the corresponding frequency spectrum for a typical specimen. The FFT algorithm produced a 0 to 1 MHz spectrum from a 500 μs time record of the acousto-ultrasonic signal.

Figure 3 shows a normalized stress wave factor versus the peel strength. In Fig. 3 the stress wave factor is based upon the signal energy which is defined as the square of the amplified transducer output voltage integrated over the time of the sweep. The SWF value represents the average of twenty-eight measurements for each group of four equal specimens (seven measurement per specimen) and the corresponding peel strength value represents the average of four measurements for each group of four equal specimens (one measurement per specimen). The straight line was obtained using the least squares method. The corresponding correlation coefficient, r, is 0.83.

Figure 4 also shows a normalized stress wave factor versus the peel strength. Following Govada et al. (1985), the stress wave factor is defined in Fig. 4 as the root mean square of the power spectral density. Again, as in Fig. 3 each stress wave factor represents the average of twenty-eight measurements for each group of four equal specimens and the corresponding peel strength value represents an average of four measurements for each group of four equal specimens. The straight line was also obtained using the least squares method and the corresponding correlation coefficient is 0.75.

Both Figs. 3 and 4 clearly indicate that the stress wave factor is correlated with the peel strength of steel-rubber bonding. Apparently, the injected signal relies on the signal path into the steel plate through the adhesive bond between rubber and steel, and re-emerges at the receiving probe through the bonded area. For weaker adhesive bonds, the transmission into the steel plate is also weaker, and the injected signal is trapped in the rubber layer and rapidly attenuates. Therefore, the feasibility of using the stress wave factor technique is nondestructive evaluation of the adhesive bond strength between rubber sheets and steel substrates has been demonstrated.

Apparently, the stress wave factor based upon the signal energy gives a better correlation coefficient with the peel strength than the stress wave factor defined as the root mean square value of the power spectral density. To improve the correlation coefficient between the stress wave factor defined as the root mean square value of the power spectral density and the peel strength it is recommended to calculate the stress wave factor using different filter bands of the acousto-ultrasonic signal as reported by Kautz (1985). Furthermore, for practical applications where large areas are to be nondestructively evaluated, it is recommended to use a moving average of the SWF measurements obtained using a dry-coupled wheeled sensor fixture similar to the one reported by Rodgers (1983).

Acknowledgements

The author wishes to thank Mr. Alex Vary, of the Structures Division at NASA Lewis Research Center, for the useful discussion and suggestions of this work. The author is also grateful to Professor L. A. Bergman, of the Department of Aeronautical and Astronautical Engineering at the University of Illinois, and to Mr. J. H. Bucksbee, at Lord Corporation, for manufacturing the peel strength specimens.

Table 1 Rubber-Steel Specimens with Controlled Adhesion

Specimen Type	Number of Specimens	Adhesive: Primer Cement	Adhesive: Cover Cement	Controlled Defects: Three Masked Longitudinal Stripes	Controlled Defects: Four Masked Squares	Controlled Defects: One Masked Longitudinal Stripes	Controlled Defects: Bond Contamination
1	4	Yes	Yes	—	—	—	—
2	4	Yes	Yes	Yes	—	—	—
3	4	Yes	Yes	—	Yes	—	—
4	4	Yes	Yes	—	—	Yes	—
5	4	Yes	Yes	—	—	—	Yes
6	4	Yes	No	—	—	—	Yes
7	4	Yes	No	—	—	—	—
8	4	No	Yes	—	—	—	—

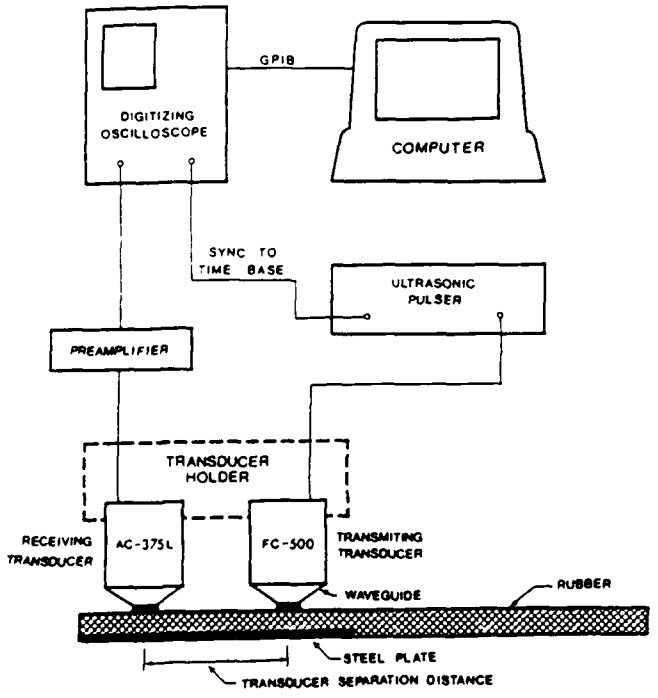

Fig. 1 Schematic diagram for the acousto-ultrasonic stress-wave-factor measurement system.

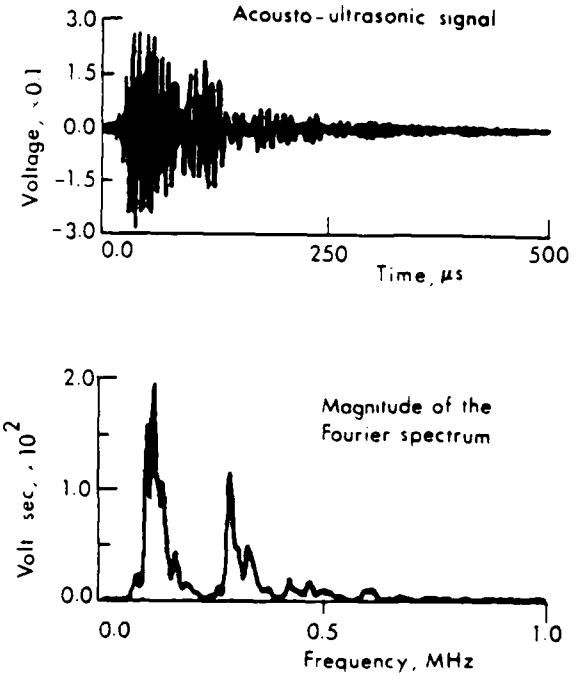

Fig. 2 Acousto-ultrasonic signal and the magnitude of its Fourier spectrum for a typical specimen.

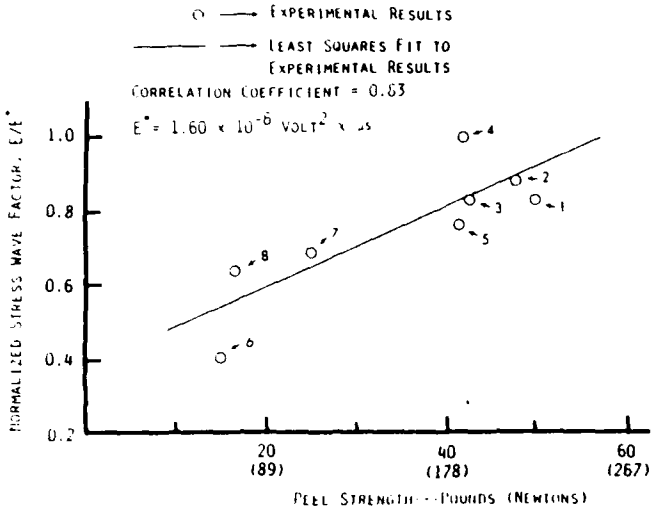

Fig. 3 Normalized stress wave factor, E/E°, vs. peel strengvth for rubber sheet bonded to steel.

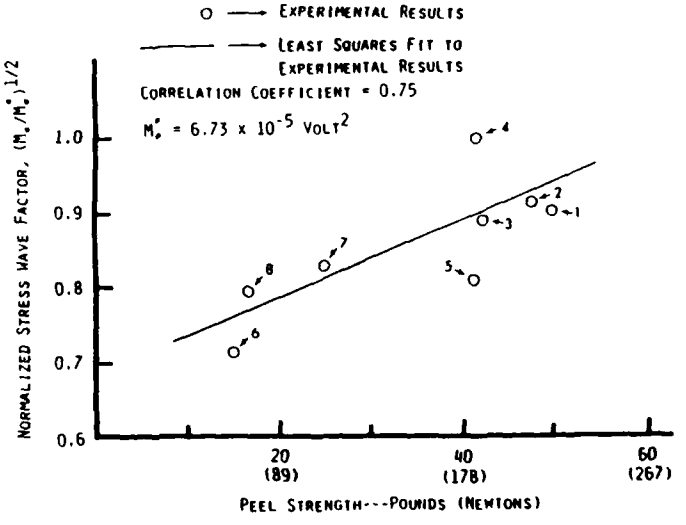

Fig. 4 Normalized stress wave factor, $(M_d/M_o^*)^{1/4}$, vs. peel strength for rubber sheet bonded to steel.

John Rogers
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ACOUSTO-ULTRASONIC DETERMINATION OF BOND STRENGTH

I think we're going to rapidly saturate your interest in acousto-ultrasound here this afternoon but I think it's appropriate since the technique is showing quite a potential for adhesive bond strength evaluation. Just a couple of insights. First of all I am a commercial producer of equipment and I hope that any of the slides* I show you involving commercial equipment are not going to be offensive. One of the reasons that I asked George to be involved in this presentation is that we are always involved in a lot of applications-type programs, development and equipment development, that are not generally reported at these kinds of technical sessions. I wanted to give you some kind of a flavor for the kinds of programs that are going on and the equipment that is being developed for commercial applications so that you'll see that this technique really is and has become viable as a production inspection technology.

Another insight into this is that there's been an incubation period here for this technology called acousto-ultrasound which started with Alex Vary at NASA Lewis back in the late 70's, and this incubation period has been associated with a general acceptance of the fact that you can measure material or engineering properties with a nondestructive method as opposed to simply looking for imaging or quantifying extrinsic defects. I think that message has been put across very eloquently here by the last couple of presenters about its potential for actually being used as a structural integrity methodology for something to look at the bond strength of materials. So with that I'll get into my presentation and I hope this is not going to be too redundant since we've already had a couple of papers on the subject. I wanted to just introduce some basic principles again of acousto-ultrasound and how it's used.

First of all, acousto-ultrasonics is the stimulation and analysis of interactive multimode stress waves for material property characterization. What do we mean by that? We mean that we are introducing stress waves into a material in a fashion that results in multiple modes of ultrasonic waves transmitting through the material. We're measuring that stress wave propagation in the

*No figures are included with this transcript

principal load directions which means that the sound waves are having to take the same path that loading would take in the structure and this is very key to the measurement. Those kinds of factors that interrupt acoustic sound flow through a material will also be those things that trap and concentrate stresses in loading of the structure. So if you look at it as a transfer function, we have a sending transducer which is injecting an original signal and we have the material microstructure modulating the signal. The signal that comes out is then received and analyzed by various techniques that you've heard described as stress wave factor in various ways.

One of the things we are trying to do in this technology is come up with some standard terminology and in fact there is an ASTM E704 committee that will start meeting next year to attempt that standardization. So a lot of factors involved in the material itself can result in modulating that signal such as coupling, reflection, diffraction, dispersion, absorption, and scattering and these are associated with not only the natural structure but also the defects within the structure of the material. So this is a way more of looking at the microstructural interactions of populations of defects as opposed to necessarily looking at single large extrinsic defects.

Now for example, if we use a fairly broad band, highly damped ultrasonic sensor to introduce a signal into a composite laminate, you might see an ultrasonic input signal that looks something like this and at some distance away, if you receive this with a typical resonant acoustic emission sensor, you see a much more enriched signal that has multiple modes and some fairly interesting frequency content associated with it. But there are definite reflections and mode separations that occur here but in general what we're doing is measuring the gross energy in some fashion that gets from one point to another in the structure and relating that to material properties. Atypically this inspection can also be performed from one side and this is just an example of a dry coupling wheeled sensor fixture that's been designed for this purpose where there is a fixed internal hub with a sensor in it. It's usually an undamped acoustic emission type of sensor which means it has some resonant properties to it and it's coupled through an external rubberized O-ring into the part. You can see from the design of these wheels that in fact there's some physical limitations to how much that rubber can be compressed because the harder you would press on an unlimited type

of wheel structure here, the more signal you would get through this rubber to material interface. So this is one of the controls that we use.

Probably the greatest limitation we have in this technology right now is the need for effective and consistent coupling. It's not quite as critical in conventional ultrasound but here it is, especially if you're going to measure attenuation properties of the material. Now the signal was injected and gets reflected in various modes and can often be mode converted. For example, if this were a fiber laminate you would see guided waves in the fibers now predominating the signal. You would also see reflected waves and these result in the rather complex shape of the final signal. This is an example of a commercial instrument, the 206, and a view of the wheeled fixture that might be used in a hand-held operation mode. You can see up here the shape of the signal is very much like an acoustic emission signal which is why we ended up using conventional acoustic emission signal processing techniques to quantify this signal. And generally those are energy related.

Summarized examples discussed:

(1) Work from Vary and Lark at NASA Lewis that shows the stress wave factor versus the ultimate tensile strength which is really the interlaminar shear strength of a group of graphite epoxy specimens. This is actually a space shuttle case section here which is a steel outer case combined with a rubber inner liner into which the propellant is then poured, and one of the primary inspections problems here is inspecting the rubber to metal bonded interface. This was just done with a little utilitarian fixture here in our hand scanning mode and this shows the results of the inspection that was done again in a hand scanning mode, so it probably could have been much more highly accurate in an automated mode of inspection. What was done in this is this sample was specially bonded up with a tab specimen between the rubber and metal and that tab was then pulled out to create an artificial delamination in this area. So I scanned back and forth across here and produced this kind of an output and you can see here's where the delamination was created. By the way, this was inspected from the metal surface because in actual practice that's the only one exposed for inspection. You can see that that delamination indicated here by the rise in the signal at this point, now this is rather interesting because in most cases in

acousto-ultrasound, when you have a defect such as a delamination or impact damage in a composite, you see a reduction in the signal. In this case we have noted when the material into which the signal is introduced and received is much more highly sound conductive than the adherend material, that in fact when the adherend is not properly bonded to the back side the signal will go up. So it would be rather convenient in a, let's say a combined laminate where you had both damage in a, let's say a composite layer and in a bond line between that and another type of material below, you'd be able to see the signal go in different directions in terms of energy or amplitude depending upon the kind of defect being generated. There are also some other areas down here that were highly suspect, they didn't tell us whether or not they had put any defects in that area and I had no separate confirmation of it but from the kinds of patterns developed here, it's quite clear that there must be some kind of delamination or weakened bonding back in this area as well.

(2) An example of impact damage on graphite epoxy. A fairly thick laminate structure, about 1/2 inch, 0-90°, ±45° quasisotropic and it was impacted at different energy levels and then two different techniques were used to analyze the extent of the damage.

(3) An example of a scan of a metal-to-metal bonded structure, I believe in this case this was aluminum bonded to tantalum for a space application with areas of weakened bonding or known delamination that could be verified with other techniques.

(4) An application which has to do with copper cladding bonded on to a laminate structure for printed circuit board production. Concern is about the quality of this bond because if the bond is poor and it gets downstream in manufacturing, when they start applying the solder joints to it the copper will lift off of the laminate and of course the board will then be rendered inoperative. We've got a series of specimens here with fixed peel strengths and this shows the acousto-ultrasonic signal level which is one of the methods we use. It's an RMS type technique versus the peel strength of the copper to polyimid laminate and it does check out very well. I might add that we were not able to get this same correlation from the polyimid laminate side. It suggested that we had to be on the copper side in order to get this correlation.

(5) An application that is being developed. It has to do with fusion butt welded pipe joints primarily used in gas transmission pipelines. A scanning fixture here that will rotate around the butt weld joint has been developed. Now this is technically not an adhesive bonded joint, but it is a chemically bonded joint having come from a hot state to a final bonded joint.

(6) Probably the best example of a commercial success of the acousto-ultrasonic technique is something we call Aubem*, it's a product that we've just introduced with Weyerhaueser Company based on a four year extensive program for the determination of internal bond strength in composite wood products. This is primarily particle board, medium density fiber board, and oriented strand board type applications. These are basically wood chips or fibers that are mixed together with an adhesive and put into a large multi opening press, they're exposed to temperature and pressure for a period of time and they come out in cookie-batch type fashion as bonded products. This product was developed primarily for the determination of the internal bond strength of that material. This is critical to the performance of these products and is also one of the ASTM-mandated inspections that has to be done periodically on these products.

That concludes my presentation, I hope I've given you some flavor for the kinds of engineering projects that are going on in acousto-ultrasound and I think you are going to find a lot more in the future. I hope that as a result of these presentations, you become a little bit more convinced that this is an up and coming technology and it certainly deserves its place among the arsenal or tools of NDE for determination of material properties. Thank you.

*actual spelling may be different than shown

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ACOUSTO-OPTIC METHODS FOR ADHESIVE BOND INTEGRITY STUDIES

While it seems acousto is the word of the day here, at the INEL we have what we think is a little bit different approach to studying adhesive bond integrity. We have a non-contacting method of both detection and excitation. The work has been funded by NASA and in part by the Army Materials Technology Lab. To give you a brief overview or perhaps a preview of what I'm going to talk about, what we're basically doing is exciting a material using either an audible click or a Q-switched neodymium YAG, then we're looking at the harmonics of that material and studying the dynamic response to that energy input. We're using two sensors in that work, the first of which is a frequency stabilized helium neon laser. We're using that as an optical transducer, it's a novel usage of this particular laser. It's really been established for a stabilized output for long coherence lengths but we use it in a different manner for a displacement sensor. It has an advantage that it works extremely well on diffuse surfaces but it is limited to a detection bandwidth of about 50 kHz. The important thing to note there is that we're really not detecting ultrasound. We don't have to worry so much about that low frequency cutoff, in fact 50 kHz is quite good for most of the things that we're doing. The second, for lack of a better term, sensor is the speckle interferometer. We use that as a means of verifying what we have detected with the displacement sensor and also as a way of studying the physics of the situation. It allows us to observe Moire patterns on the surface of the material, in other words, areas that aren't vibrating when we've excited them with a signal frequency. Quickly, to give you a little better understanding of the frequency stabilized laser or optical transducer. Within the lasing cavity or within the resonator it has two orthogonally polarized modes present at the same time. In the laser it tries to establish a stable output by monitoring the intensities of these two orthogonal modes using photodetectors at the back of the cavity as you see. In order to keep the ratio between those two modes stable, it alters the cavity length using a servo mechanism. This will tend to shift the gain curve back and forth and keep the two peaks there at the same constant intensity. If we allow one of those modes to escape the cavity, we have

OVERVIEW

- Excite material using Q-switched Nd:YAG laser or audible click

Observe harmonics of adhesively bonded material

> Changes in adhesive bondary will be evedent in changes in harmonics

Sensors

- Novel use of a frequency stabilized HeNe laser as a displacement sensor
  - Works well on extremely diffuse surfaces
  - Detection bandwidth presently limited to ~50 kHz
- Speckle interferometry for determination of nodal point locations

contingent upon a surface we are trying to inspect using a lens to focus that down on a surface. That same lens will act as a collecting optic transmitting the light back into the laser cavity which will tend to destabilize the laser. The servo mechanism will then try to maintain a constant intensity ratio between the two modes. We strip off the servo signal and look at that. It turns out that that is a measure of the displacement of the surface.

For the talk today, I'm going to discuss briefly two different types of materials that we've been expecting with this, the first of which is the thermal protection system tiles on the space shuttle orbiter and the second are adhesively bonded composites that have been pre-cured, in other words, fiberglass, graphite that has been pre-cured and then adhesively bonded together.

First, the tiles have a structure similar to this or an adhesive bond line similar to this. The tile itself comes in all shapes and sizes but for the largest part they are about 1"-1 1/4" thick, 6" on the side, very light and porous so that it's difficult to inspect them with any other means and they are also very fragile on the surface. Below the tile you have an RTV adhesive bonding the tile to a strain isolation pad which is a felt-like material. This is in turn adhesively bonded to a substrate which in practice would be the skin of the space shuttle.

The experimental setup then is to excite that tile using an audible click from a speaker. For this work we're using a 100 microsecond click which gives us a broad frequency excitation for the tile at 0-10 kHz. We detect that with the frequency stabilized laser, capture that data, digitize it and store it. Here is a picture of the actual experimental setup. The frequency stabilized laser is a small blue laser there in the foreground. The speckle interferometry then is in the background, you see a couple of beam splitters there. Here we have the frequency stabilized beam, a mirror used to redirect that beam to the tile which would be back here. Speckle interferometry setup consists of a larger helium neon laser, the beam splitter for recombination of a object beam and a reference beam which comes across here and back. Back to the frequency stabilized beam, here are four unaveraged sets of data time series taken from one of the space shuttle tiles. You see very good agreement and very good repeatability between each set of data. As one might expect, a simplistic view of what is occurring is

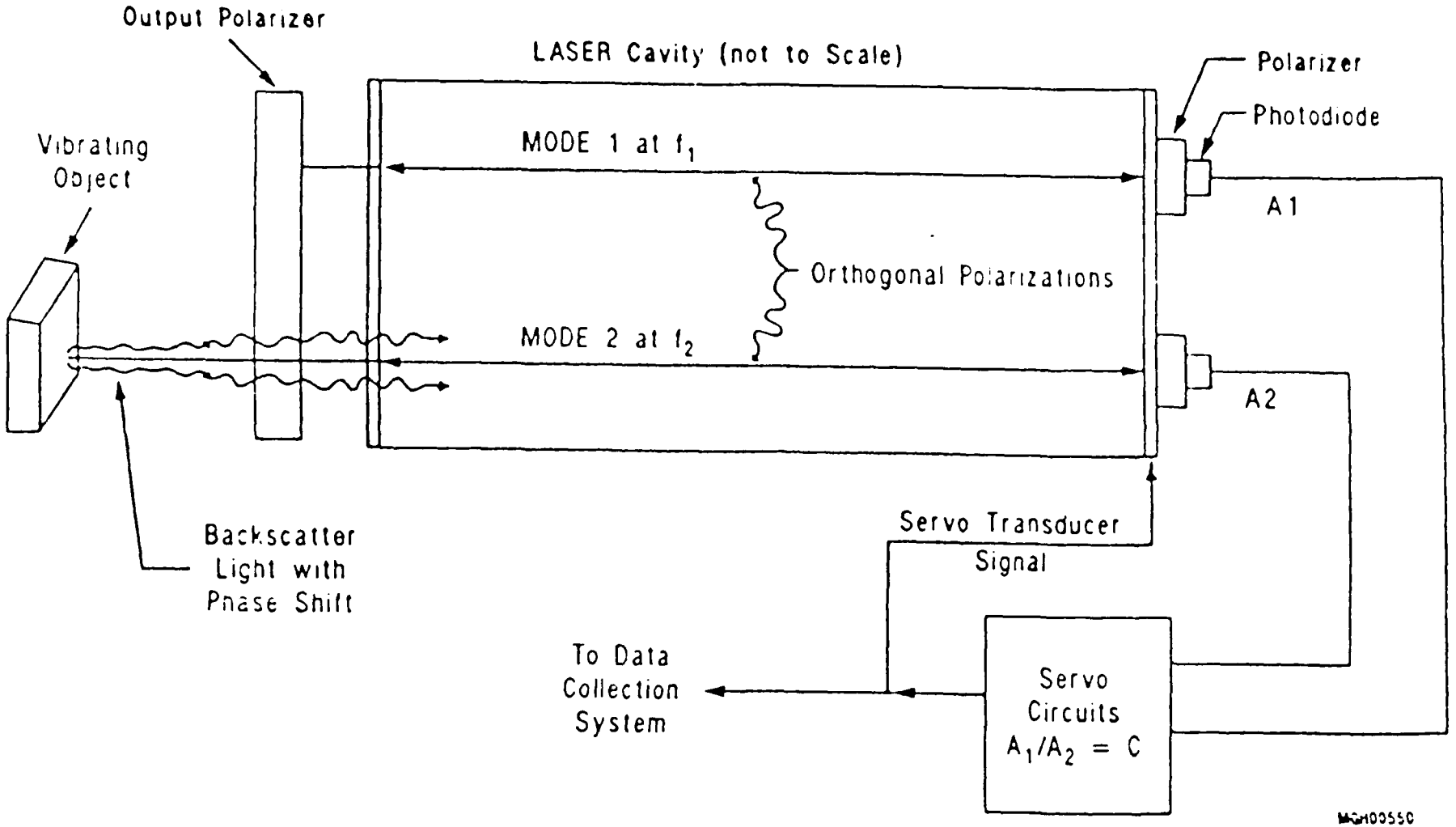
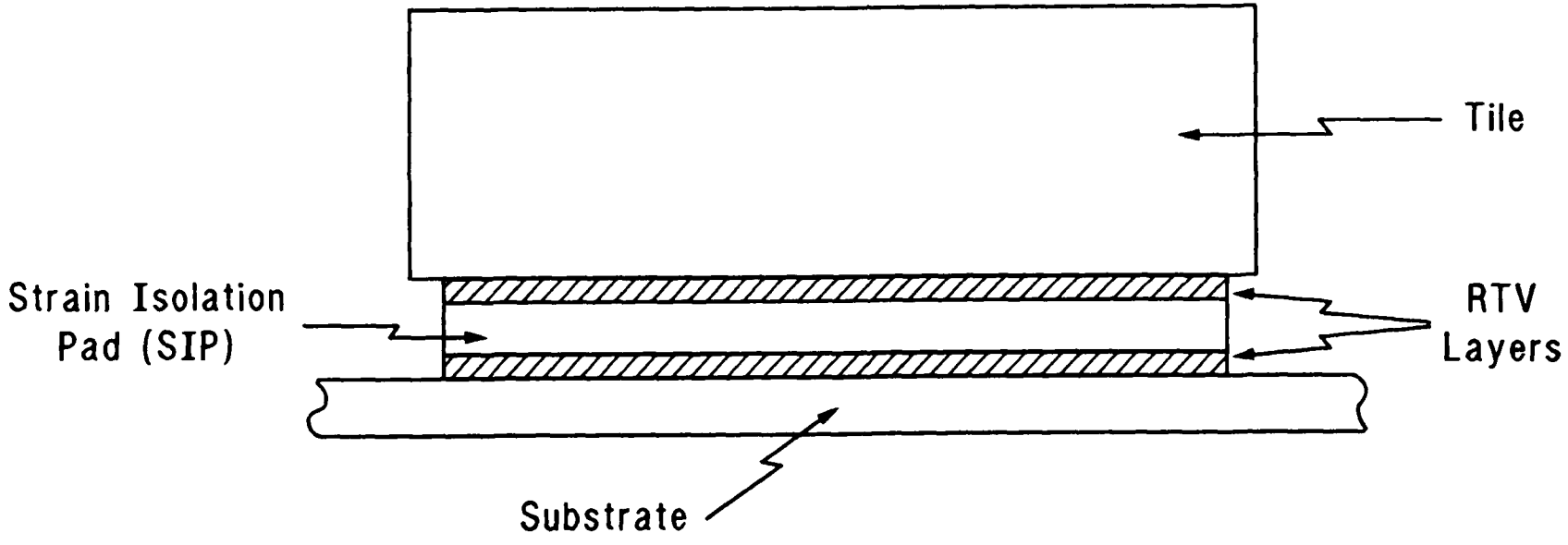


Figure 1. Stabilized LASER--concept of operation.

Types of Materials

- Thermal Protection System (TPS) tiles on space shuttle orbiter
- Adhesively bonded pre-cured composite

Tile Adhesive Bond Structure



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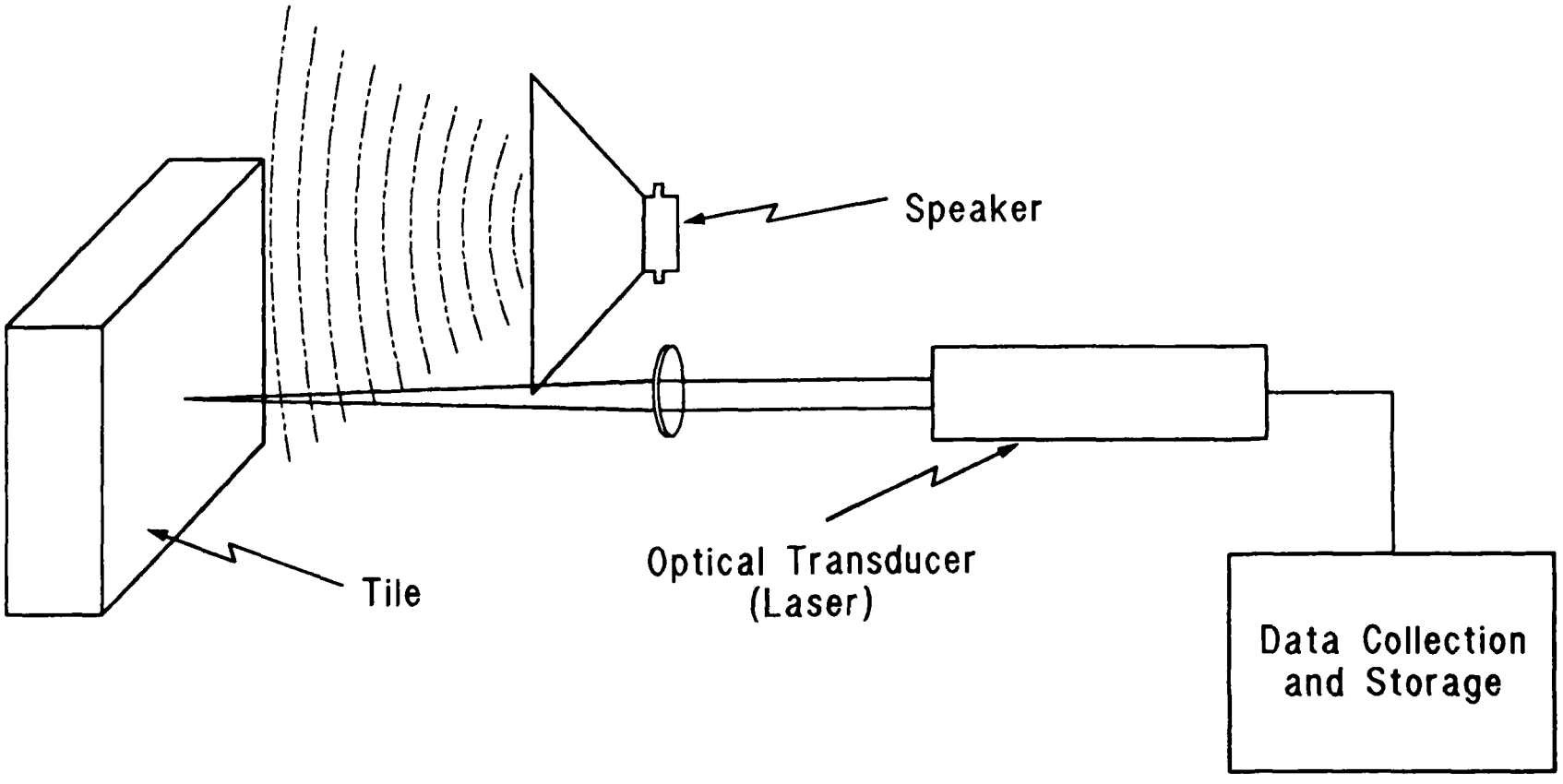
Experimental Set Up



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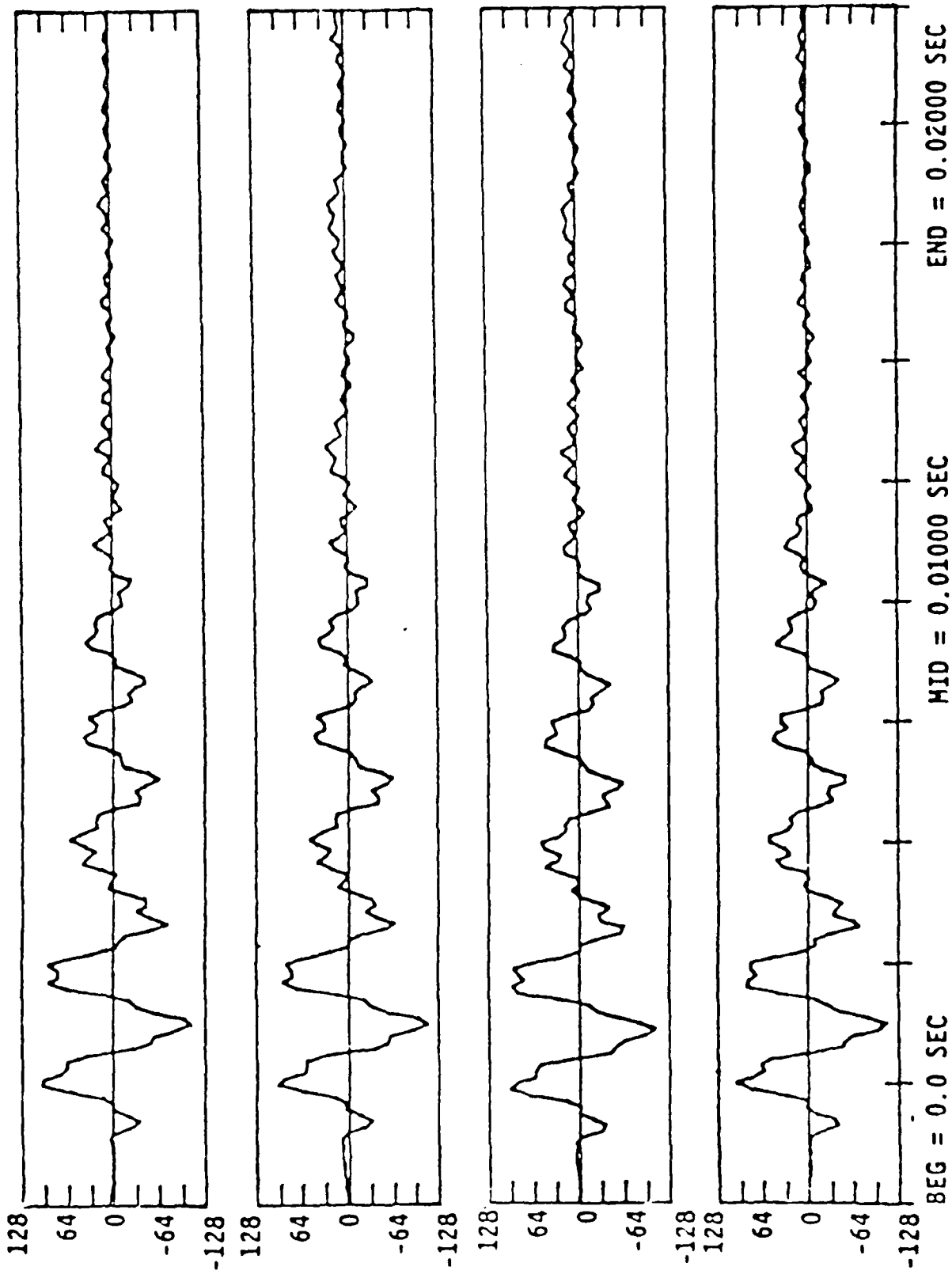


Figure 4. Four sets of unaveraged laser data files.

that as that tile becomes more and more unbonded, the frequency shift or the resonances of that tile are going to shift to lower and lower frequencies and as you can see here, starting at the top, we have no unbonding condition in the tile. Moving down towards the bottom where we have a greater degree of unbond you see that the lower frequencies are indeed picking up and that the higher frequencies are dropping off. These are three speckle interferograms of one of the tiles. After we've gone through and collected those time series and done the Fourier transforms of those we can go back and look at the actual resonant modes of the tile. On the left you see, right in this area is a null pattern, in other words, this area on the tile is not vibrating under that 370 kHz single frequency input. As we unbond at once we see a stripe begin to form here where the tile is now vibrating in a different modal pattern and again after we unbonded the second time we see another modal pattern here. It may be a little easier to see on the next one. Here's a higher frequency excitation of the same tile as we go through the same sequence of unbonds. Here we have an oval pattern, this area not vibrating, the lighter colored area. It begins to elongate as we unbond and then it becomes extremely elongated towards the last unbond.

The second material I talked about was the adhesively bonded precured composite. Here we have another experimental setup (no Figure available). We have the frequency stabilized beam here impinging upon a sample which is clamped in this structure. Here we have the focusing lens. In this case it's 100 mm focusing lens but recently that's sort of an aside, we've been able to configure optics that allow us to get as far away as 30 feet from the sample and still collect nice very repeatable data from it. Behind it you see the Q-switch and neodymium YAG laser and it's important to note that though we have it impinging on the back surface here for excitation purposes we could just as well have it on the front surface. It's a little easier to make the experimental setup with it on the opposite side. And also the photodetectors in the HeNe will detect that infrared radiation coming from the YAG so it would need a hot mirror in front of the HeNe for that.

This sample has two flat bottom holes, one here and one that you can't see over here. Because the structure of the materials is much more complex than what we were dealing with in the tiles, we first went to an ideal sample, what we call the baseline sample, giving us perfect data. It's an aluminum sample with flat bottom holes drilled in it, varying widths of the holes that you see there.

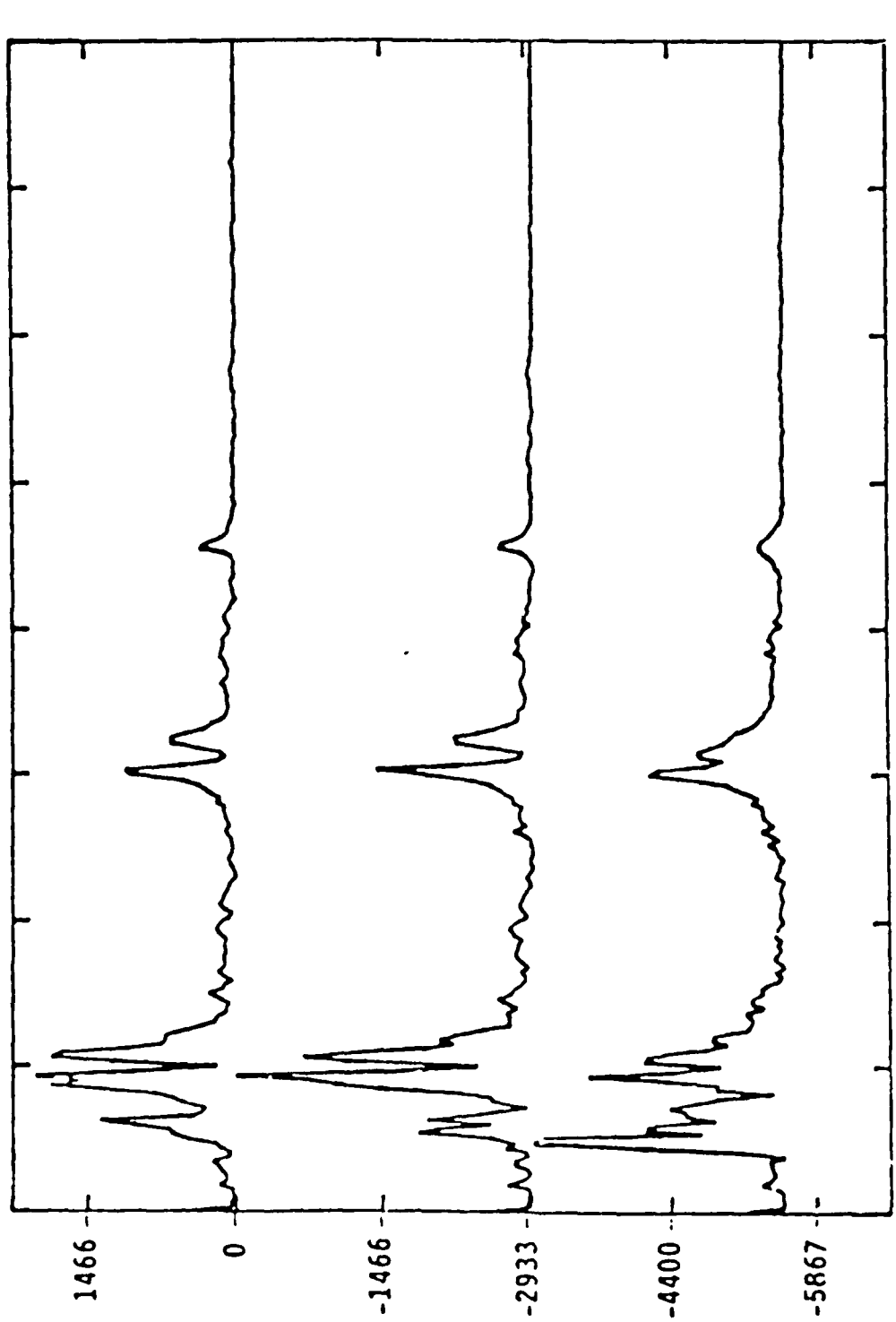
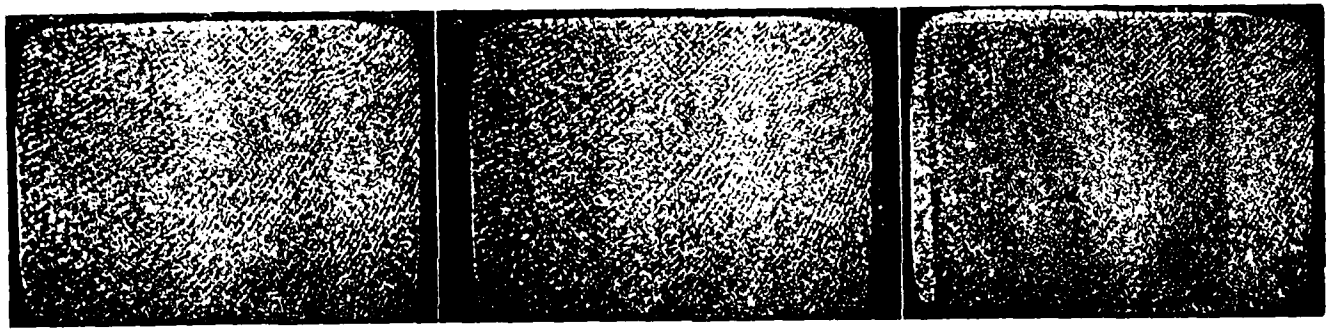


Figure 14a. Tile 8122 TC point--Spectra during unbonding.



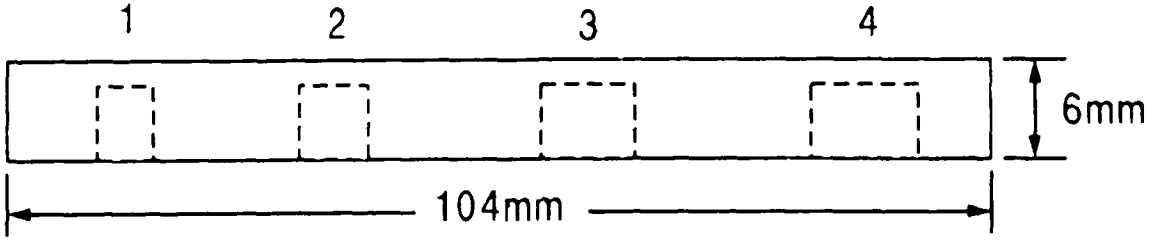
0 UB* 1 UB 2 UB

Figure 26. Tile 8122 modes at 370 Hz.

* UB Refers to unbound

Figure 27. Tile 8122 modes at 2000 Hz.

Baseline Sample



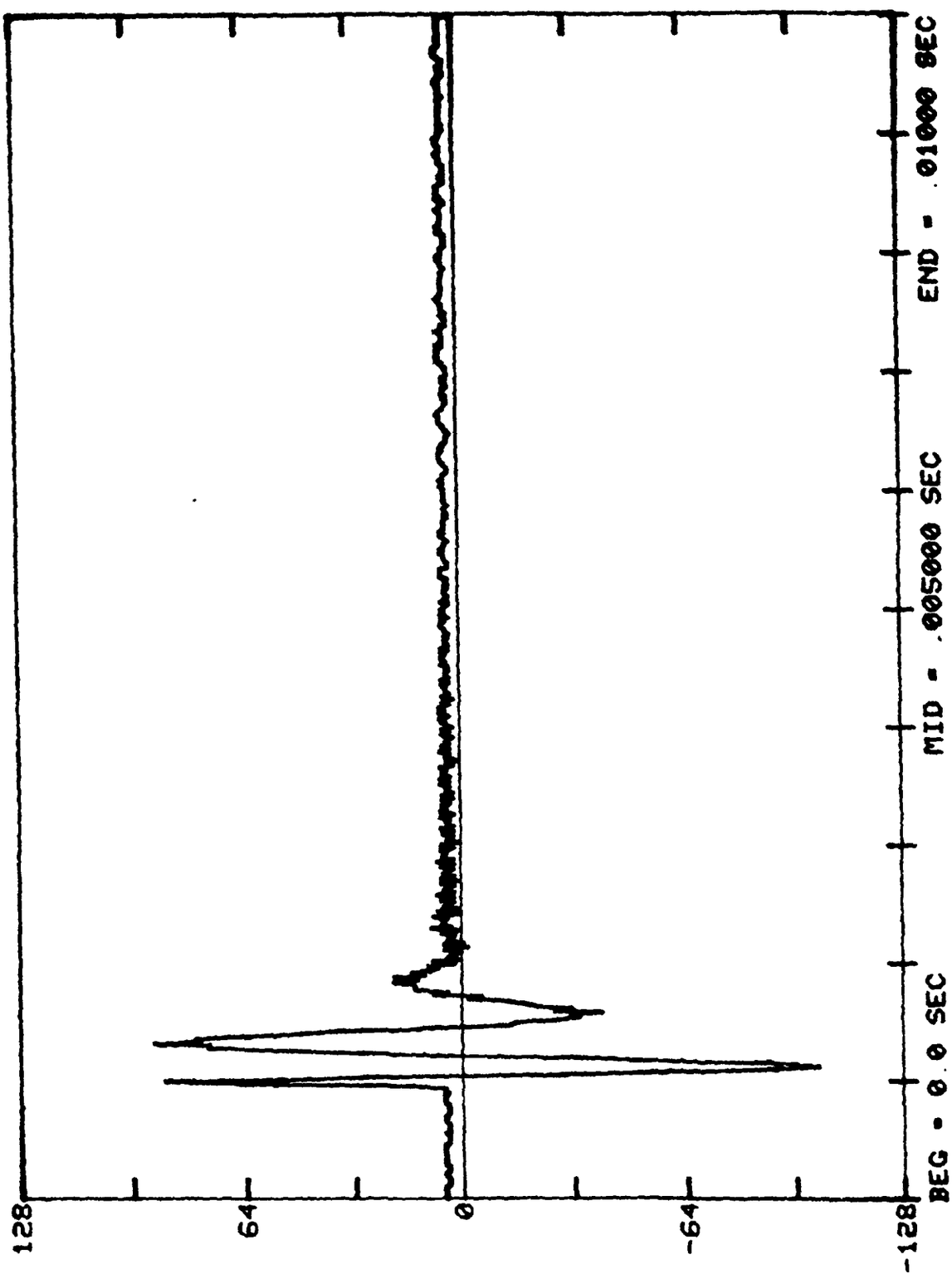
Aluminum Sample FBH Dimensions		
FBH	Dia.(mm)	Skin Thickness(mm)
1	8.052	0.229
2	10.800	0.229
3	12.802	0.229
4	14.275	0.381

MGH01636

Unfortunately, the thickness of the material above the hole is supposed to be the same for all four and the machinist made a mistake and the last one is a little thicker than it should be, but any rate it gave us a better understanding of what we were looking at. If we use the YAG to excite this on the back surface, in the beginning we have a large-scale displacement which the YAG cuts off about where the spike is here. I should say exactly how we're exciting that, we're using a burst of key switch pulses, a burst of about 5 kHz pulses every 30 to 40 ms. Within that burst there are anywhere from 4 to 10 depending on how much energy you want to put into the sample. Starting at the upper left here we have the smallest diameter hole and you can see the frequency here as it rings for quite some time after the actual excitation is taken away. As we go to larger and larger diameter holes we see that the ringing becomes a much lower frequency as one would expect. Looking at the frequency spectra from those it's exactly what you would think it would be, the only problem is the lower right is the one with the thicker surface material and it doesn't quite follow the progression of the other three.

In the tabular form (Table not available), that data shows a couple of things. One is we also used a click excitation independent of the laser excitation as another means of exciting the sample. The click in this case was a 40 μs click giving us a frequency band with 0-25 kHz although there is a filtering effect due to the speaker below kHz. The values on the right here are from the click excitation, the values on the left are from the laser excitation. You see good agreement between those two. Also we would expect that the boundary conditions around the surface of that flat bottom hole would be somewhere in between a simply supported and a clamp case which is shown with the calculations here for the simply supported disk or a totally clamped disk.

Moving on to a composite sample, the one that was in the fixture earlier in the presentation. We have an 8 mil thick steel skin which is adhesively bonded to 5 plies of graphite which is in turn adhesively bonded to 20 plies of fiberglass. The two flat bottom holes and I'm not sure you can see them, there's one here and one here. This particular hole has been drilled to the adhesive bond line between the graphite and the fiberglass and we trimmed out the graphite bond. The flat bottom hole to the right here has been drilled to the graphite steel adhesive bond interface and that's termed the steel bond. A couple of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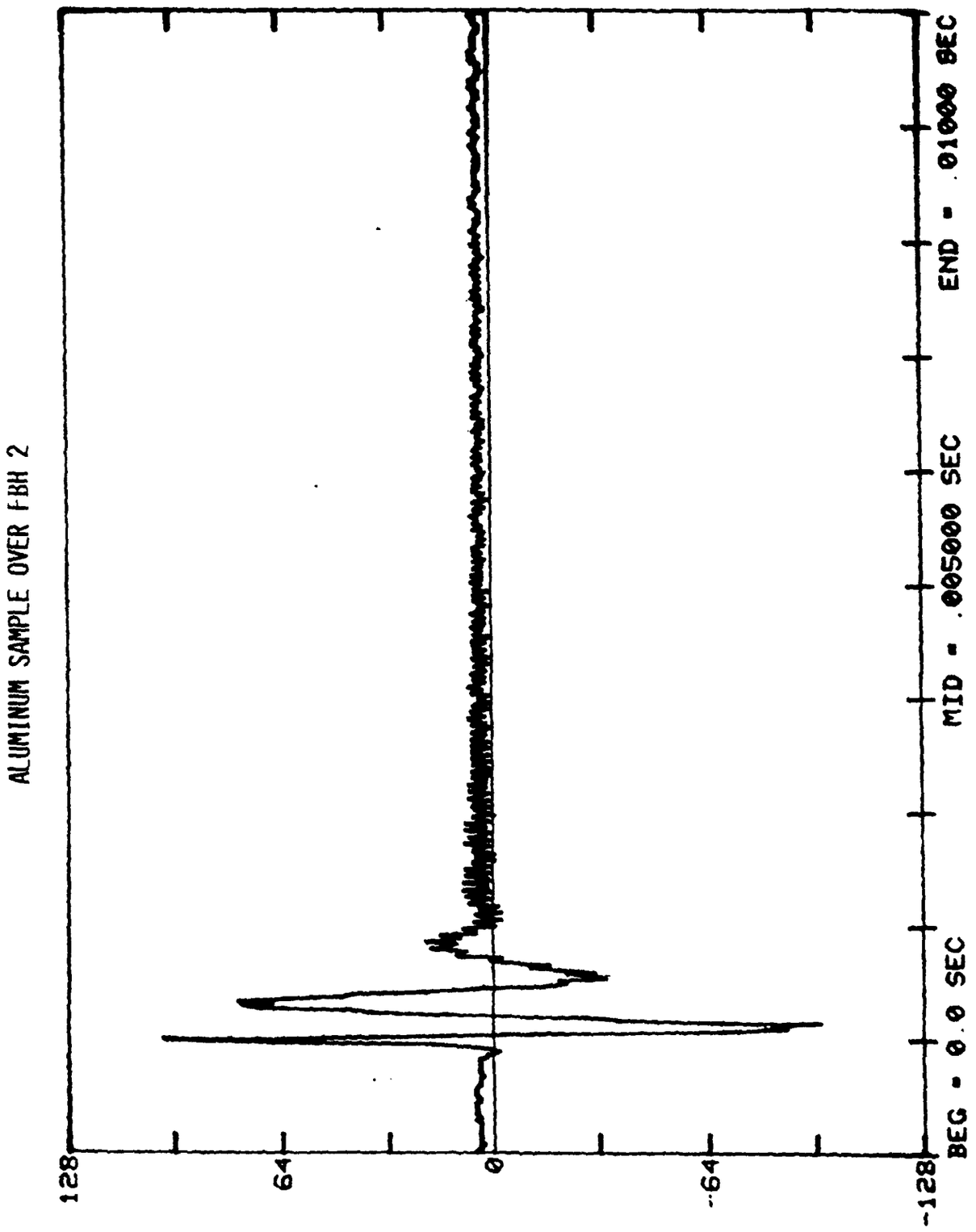
END = .01000 SEC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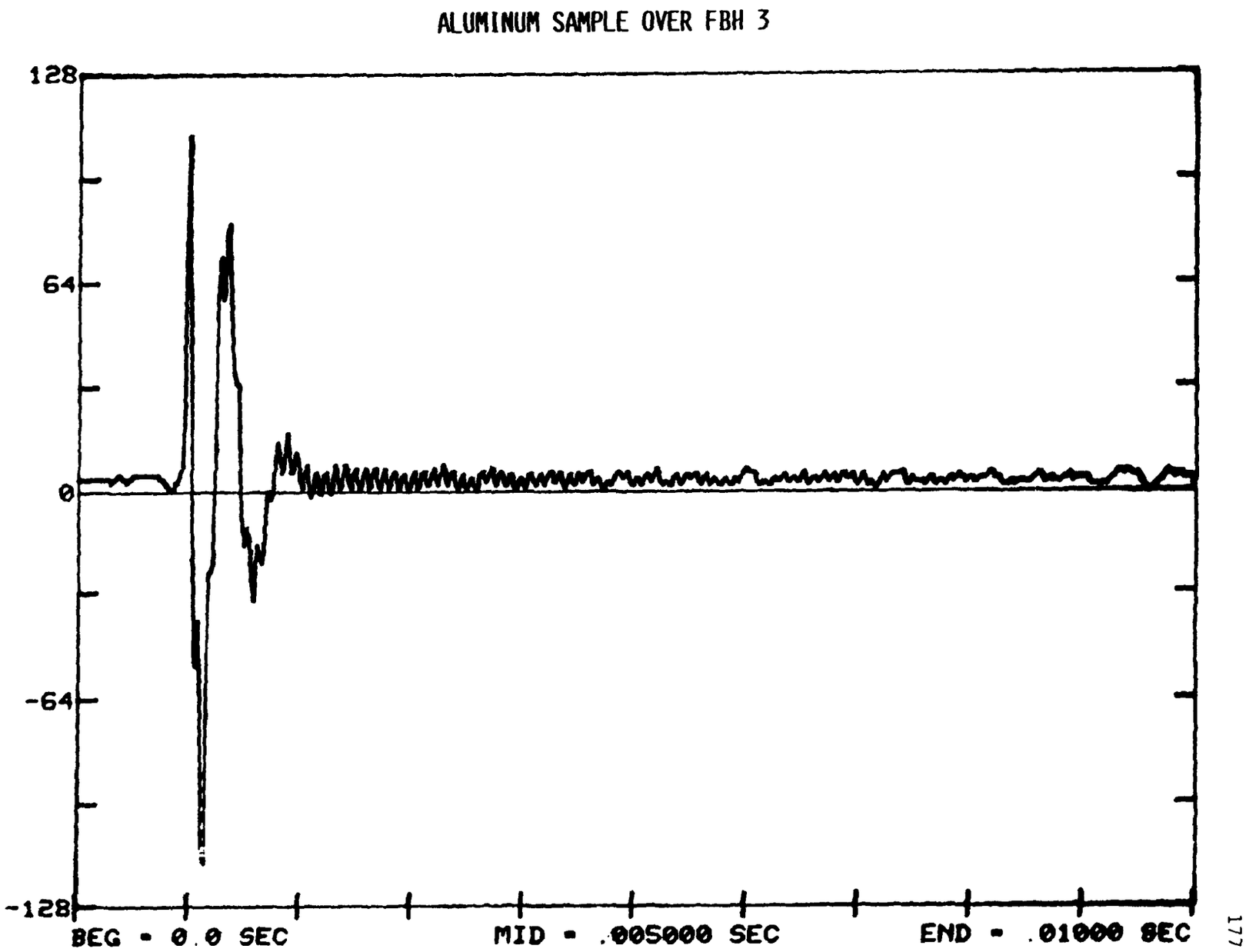
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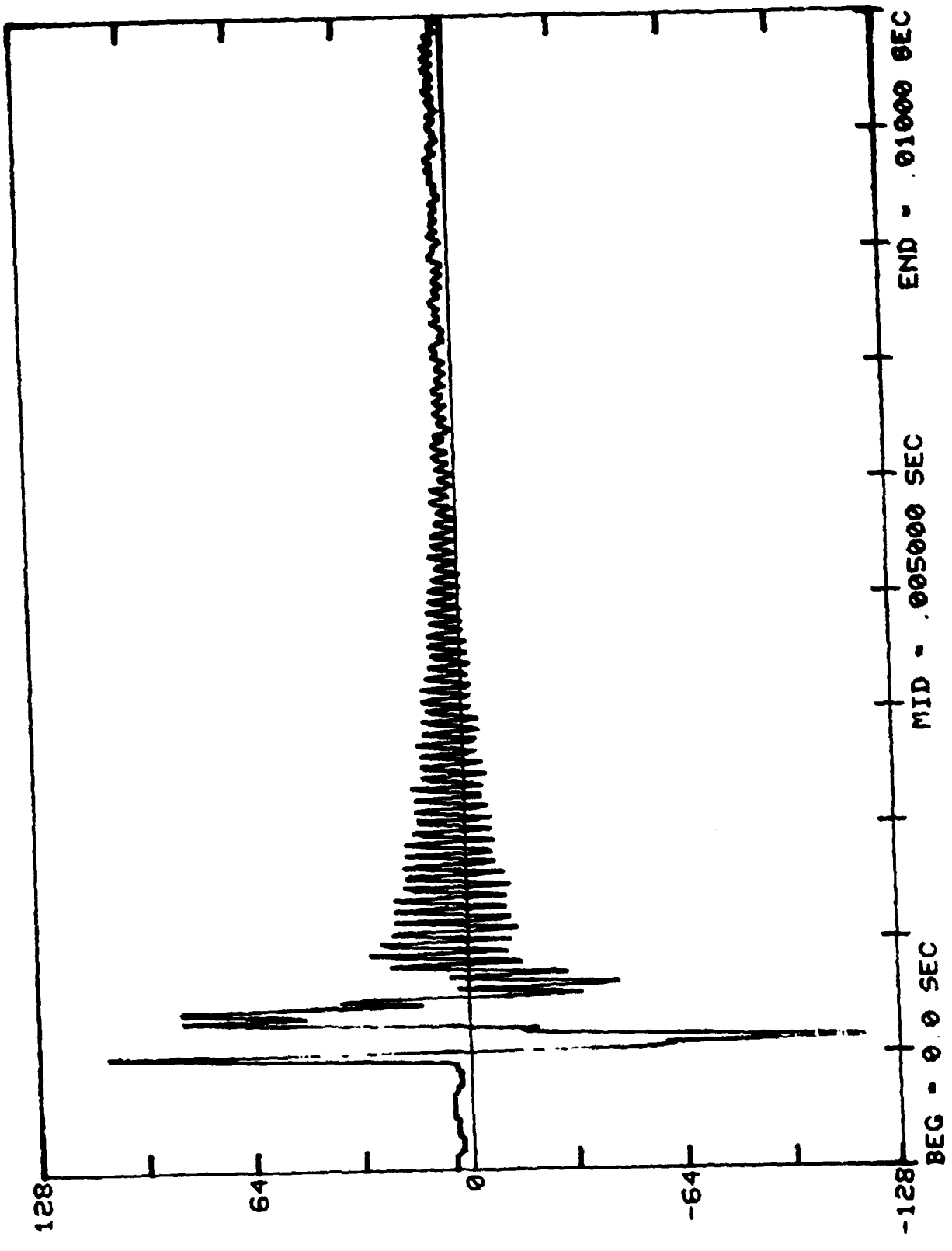
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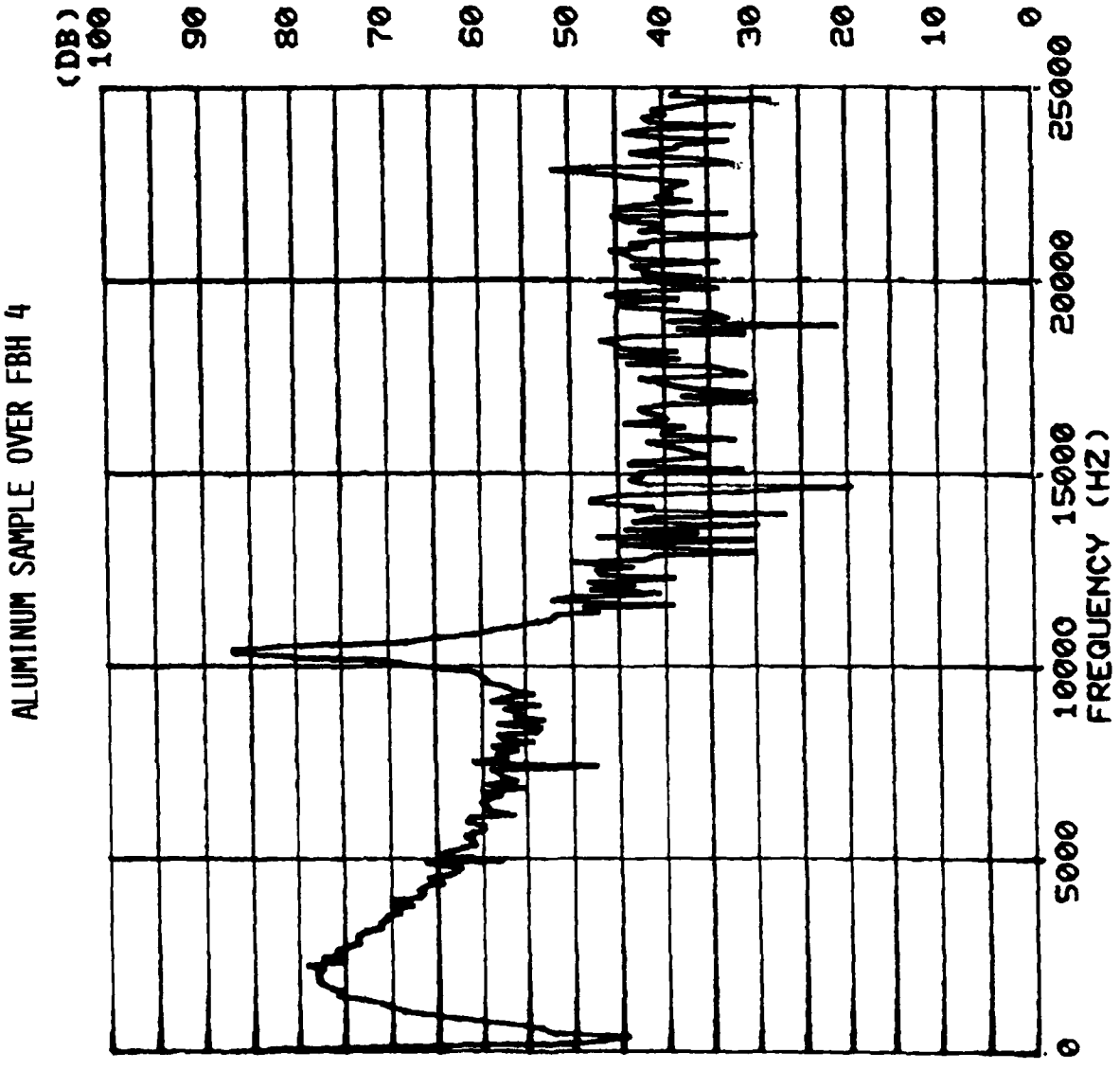
-64
-128
BEG - 0.0 SEC
MID - .005000 SEC
END - .010000 SEC


ALUMINUM SAMPLE OVER FBH 4
(DB)
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70
60
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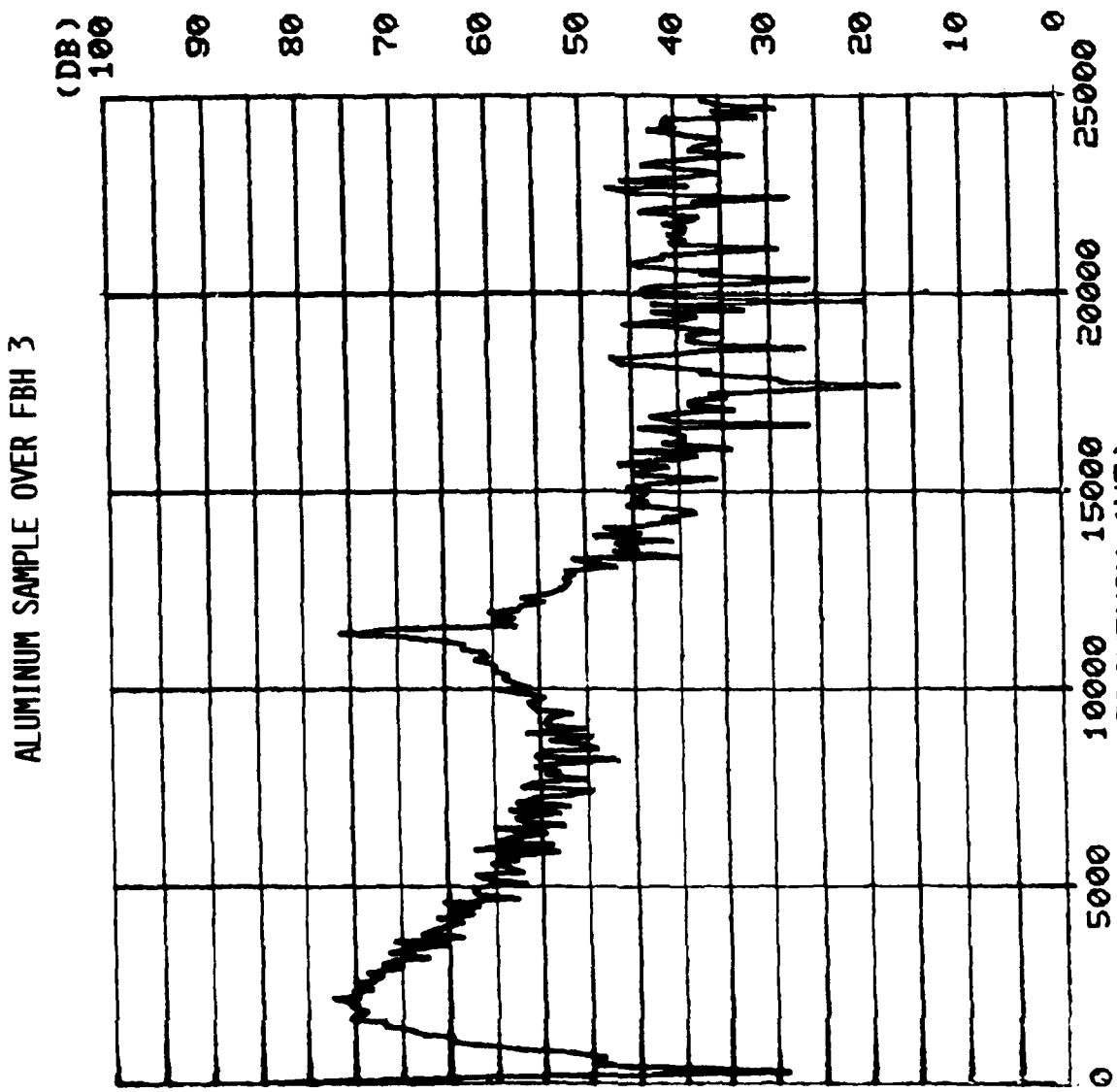
40
30
20
10
0
0
5000
10000
15000
20000
25000
FREQUENCY (HZ)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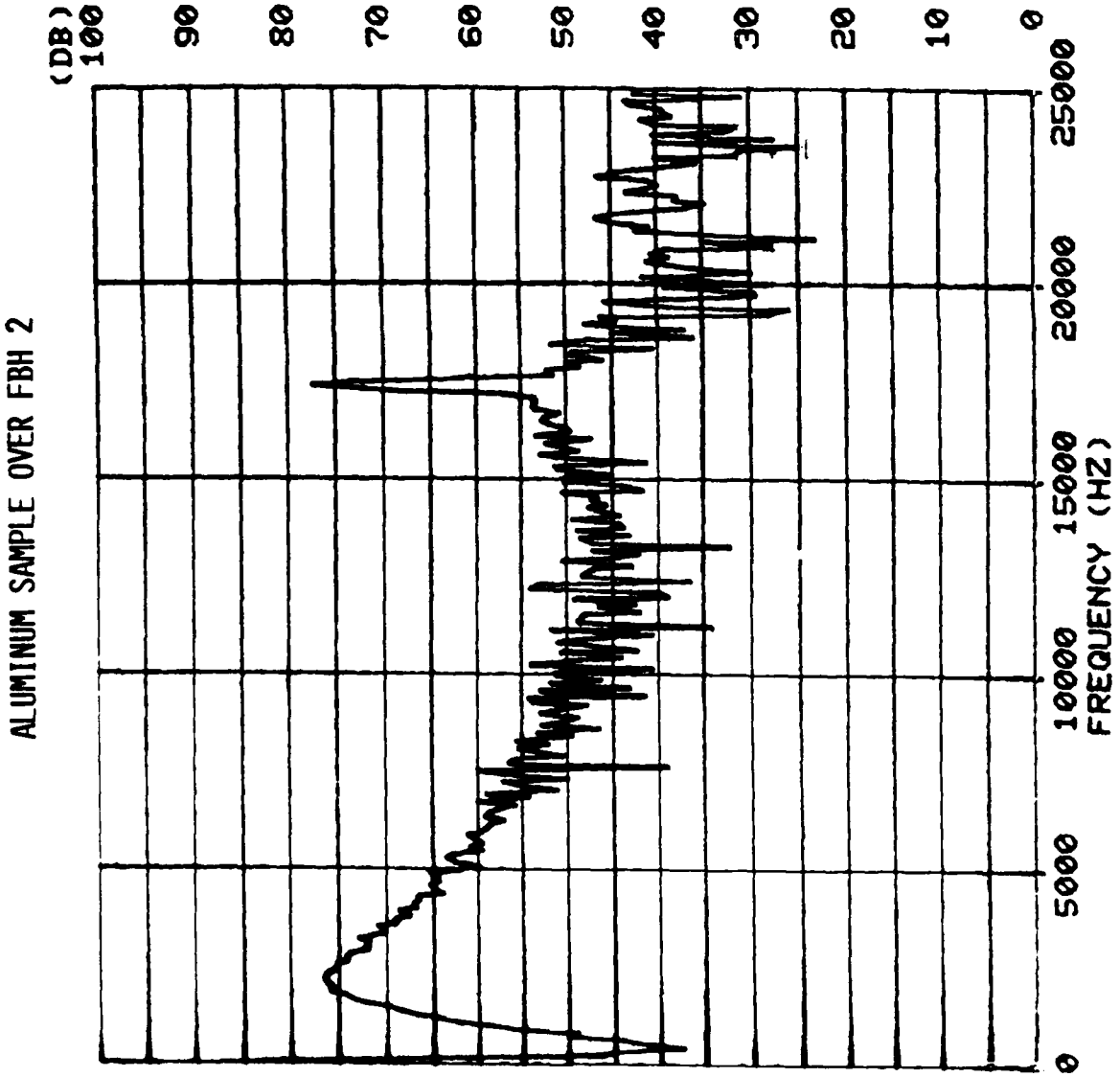
FREQUENCY (HZ)


ALUMINUM SAMPLE OVER FBH 2
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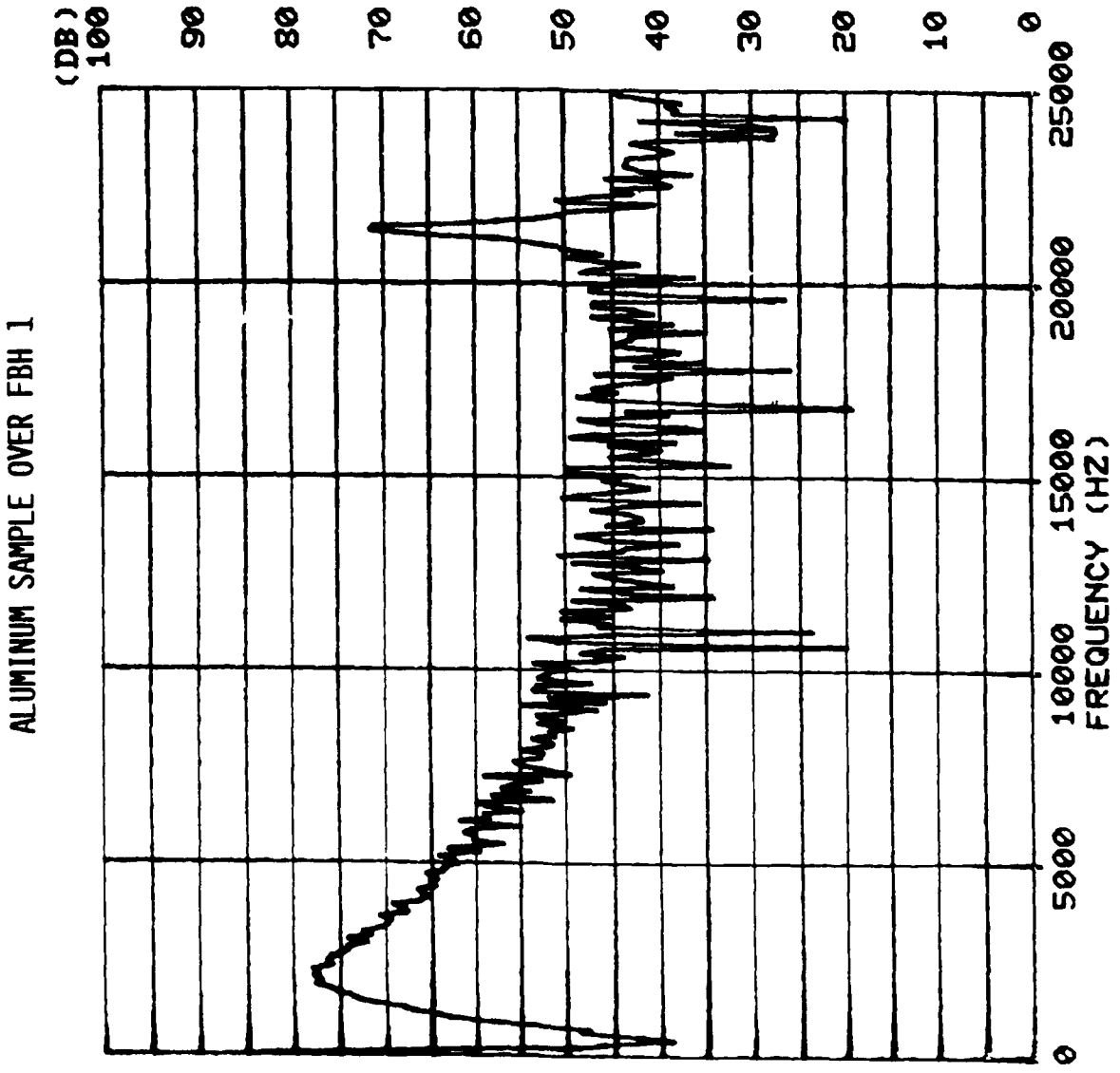
40
30
20
10
0
0
5000
10000
15000
20000
25000
FREQUENCY (HZ)

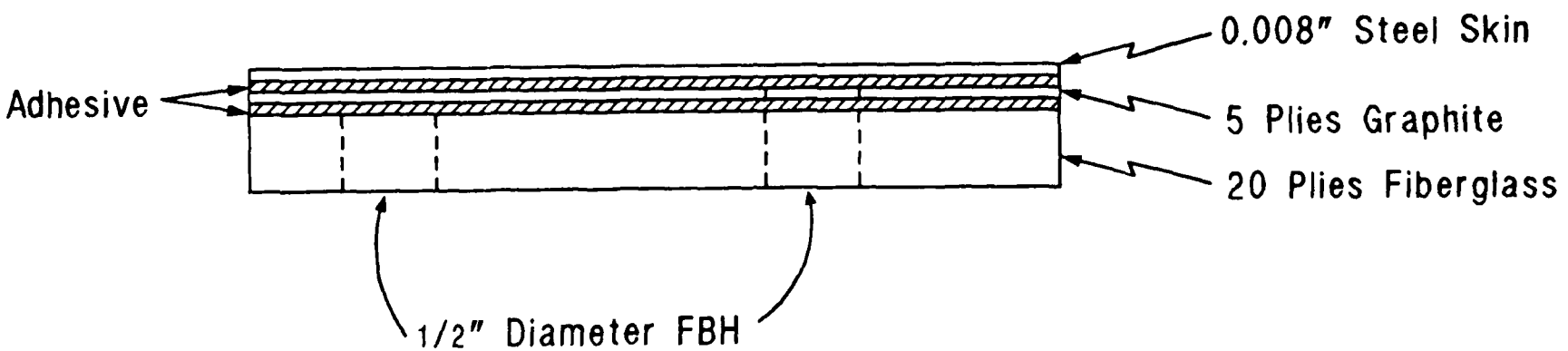

ALUMINUM SAMPLE OVER FBH 1
(DB)
100
90
80
70
60
50
40
30
20
10
0
0
5000
10000
15000
20000
25000
FREQUENCY (HZ)

Data for Aluminum Sample

Experimental Data		Calculated Values	
	Excitation	Simply	
FBH	Laser/Click (kHz)	Supported (kHz)	Clamped (kHz)
1	21.4/21.3	17.2	35.4
2	17.4/17.6	9.6	19.7
3	11.4/11.9	6.8	14.0
4	10.4/10.6	9.1	18.7

MGH01639

Composite Sample



MGH01637

things to note from the data from that. One, the laser excitation didn't work too well for the thicker material. That is probably because the energy per pulse was quite low, we were looking at around 200 millivolts per pulse and a rather long pulse, a 100 nanosecond pulse approximately. However, we did do the click excitation on the three areas, the graphite bond, the steel bond, and the material as a whole. The thing to note is that there is a significant difference shown here between the resonances of those two flat bottom holes, a drum head effect so to speak. The 3.9 and 5.6 kHz resonances are due in part to the material as a whole resonating and also some of it to the mounting fixture itself.

So to conclude we've used this technique to evaluate differences in bond quality between various materials. It should also be noted at this point that there is an extensive modelling effort underway right now on the tiles to better understand the phenomena that we're seeing there and we've also been able to use a laser generation for the harmonic excitation of the material although it needs a little refining. We could easily up the pulse energy and still be well below the damage threshold of the material. I think that wraps it up, thank you for your time.

Data for Composite Sample

Location	Laser Excitation	Click Excitation
Steel Bond	13.4 kHz	3.9, 5.6, and 12.9 kHz
Graphite Bond	Undetectable	3.8, 5.6 and 9.0 kHz
Midpoint	Undetectable	3.9 and 5.6 kHz

Conclusions

- Bonding differences are detectable for tile and composite samples
- Possible to use laser generation although technique needs refining

AFTERNOON DISCUSSION
April 13, 1988

George Matzkanin:

One thing I was wondering about is most of what we've talked about today, it seems, are primarily systems where one of the components is kind of a rigid material, a steel or a composite, perhaps something like that. In some cases we talked about rubber bonded to steel and rubber bonded to perhaps a polymer composite. I was wondering if anybody would like to comment on what difficulties might be associated both from the inspectability standpoint and maybe also Professor Brinson would comment on the situation from the adhesion science standpoint in systems where you have maybe a rubber bonded to a rubber. You know, if you have that kind of a system how can you handle it from an inspectability standpoint and even from a mechanics of materials standpoint.

Hal Brinson:

I will defer comments about inspectability to the rest of them because it's not my field. But I think the difficulty there would be that you have similar materials I assume or similar moduli but many of the characteristics of the stress analysis would still be similar. I think that from a surface analysis standpoint, of all the people that do surface analysis find it difficult to do surface analysis on the softer materials like rubber or polymers, it's easier on the metals. So that would be my comment.

Yoseph Bar-Cohen:

As far as inspectability of different than what you call the traditional polymer material that we talked about today, there shouldn't be any problem detecting unbonds unless we have a high attenuation in the case of the ultrasound. Let's face it, how many methods do we have. We have ultrasound, we have holography, maybe tomography, each one of them has its own limitations. At least tomography and holography are limited to thin top surface. If it's too thick, beyond 1 mm or 0.040", the limits of that method, beyond that you can't inspect those structures and as you know, most structures are much thicker.

That's why maybe yesterday I made a comment that actually ultrasonics is the best tool we have actually to inspect unbond because really it has a broader scope, it doesn't mean it solves all the problems but it has a broader scope. So for the case of rubber, there we have a little bit of problem. If you notice, I tested the steel to rubber problem from the steel side because the rubber is a highly attenuative material. Of course there's the choice of going into lower frequency or higher energy, high power ultrasound, that can be done but using conventional technology, it's not easy. You have to specifically look at the system that you're dealing with, in the case of the rubber or the plastic, same thing.

John Rogers:

I'd like to expand a little bit on that myself George. We've had some programs that have involved coupling to fairly flexible materials such as Teflon coated fabric used in large tent or inflated structures. You want to inspect the adhesive lap joint quality and there using a fairly low, hundreds of kilohertz, type sound wave injected again with a flexible type of rubberized membrane material was fairly successful in shooting a signal across there and there was a relationship between the quality of the bond and the acousto-ultrasonic reading. Also there's been some work done on rubber bonded to Kevlar for rocket motor cases where, I described one case situation where we've inspected from the metal side but we've also had some programs where we've had to inspect from the rubber side as well. And again through dry coupling we've been able to inject a signal through the rubber, into the laminate below and it turns out that the rubber being a very high absorber of the sound signal that there is in fact a delamination there that signal will not get through and propagate in the rubber material itself so it has to go through the bond line into the laminate and back up again where the other wheel was placed and so if you have a good quality bond you get a signal through, if you have a poor quality bond, the signal becomes less and less. In fact, one of the complications of that method is that they could actually see delaminations in the Kevlar laminate below the rubber layer and that was somewhat confusing, the indications that were purely arising from the rubber to Kevlar bond.

Speaker not identified:

I'd like to add that the same is true for laminated beams. Large trees don't exist now very often so we make big beams out of small trees and you laminate them. I just got very good results using acousto-ultrasound measuring the bond strength in these types of systems. In fact, we had included inserts of Teflon and it's very sensitive to that. We can detect the Teflon.

Speaker not identified:

My comment on this is that in any bonded structure, whether it's rubber or steel or any material, the optimum condition or the optimum situation that we should look at is that somehow we transmit our sound waves or any other NDE waves or beams through the bond line rather than across the bond line where there is more interaction with the bond. What I mean is that if the sound waves travel along the bond line in the same direction where the stress is applied, then you would be able to correlate the effect the bond will have on your sound beam with the stress which is basically again in the same direction.

Jack Duke:

I've heard a number of people use the term bond strength and I'm wondering, I'm puzzling over it in relationship to some things that I'm aware of in perhaps more traditional monolithic type materials. We hear about tensile strength, and ultimate strength, and we can talk about strength in the sense of what happens when you load something in sustained loading and it fails, we can talk about short term tensile strength or residual strength and things of that sort. I'm puzzling over whether or not it's realistic to expect to get a single value correlation between a nondestructive parameter and a bond strength, first of all, and how elastic properties and elastic property variations and the associated measure that you get related to that nondestructively would then ultimately translate to so-called bond strength. I guess it's not clear to me that everybody who's using the term bond strength is really meaning the same thing and I guess I was wondering if folks feel comfortable in commenting on when you say bond strength what that means. We teach our undergraduate students about tensile

strength and then if we talk about complex loading we talk about failure theories for complex loads and so when we talk about tensile strength, that's one thing but if you talk about bond strength and you sort of divorce that from the discussion of what the state of stress is, it's difficult to understand what the term really means. I guess I was wondering if folks could, in order to help us do quantitative NDE, it would be nice if there was some quantitative description of bond strength.

Speaker not identified:

Let me say something first and then let the rest talk about the NDE. I gather by your question that you're referring to the type of stress field that you might be measuring and I agree with you, I think the very essence of the problem is to try to find a pure stress field so that if you have a tensile stress, you can associate that with a particular value or if you have a shear stress you can associate with it, or on the other hand if you have a mixed situation that you can identify it and then relate it to a particular kind of failure in the mechanism. It's not just that, you also have to worry about the planes of failure and where the failure is, whether it's in the oxide layer or whether it's in the so-called interface or whether it's in the adhesive and I've heard an awful lot of people that do this, argue a lot about whether it's cohesive or adhesive or whatever. From a mechanics standpoint if you look at some of these problems like single lap test, it's going to fail near the singularities along the reentrant corner, it can't do anything else and then you'll get different character depending upon the quality of the adhesive whether it's ductile or brittle, and the quality of the interface, as to whether there's corrosion or some kind of moisture penetration. So it's a very complex problem but I do think you need to understand the stress field, whether it's tensile or shear or some kind of mixed mode. That's exactly why the so-called Boeing wedge test is such a good test is it's a pure test, it's pure tension and therefore gives you a good understanding of what's happening in one case. I'll let it go from there.

Yoseph Bar-Cohen:

I'd like to elaborate on some things that Dr. Brinson said. While it is not so obvious what you get for a destructive test because you have to know what you're dealing with. You add to that complexity, the wave propagation relation to that, sending a wave through the system with very little amount of energy which is not going to destroy anything, that's why it's nondestructive and you're trying to come with some numbers that tells you how strong the structure is. Now it's not clear what we are after. Is it the shear stress or the shear strength of the bond or interface because all those things are taken in the characterization of a bond. When we use waves that we send through, it is affected by many things, the bulk which you don't care when you do a destructive test because you already made sure that the supposedly debonded surface will fail, it fails elsewhere that's OK then the adhesive is OK. But for the NDE point of view we have to go through those materials to get there. By the time the wave goes there it's already had some interactions which carry information and we have to find a way somehow to screen out, deconvolve if we can do that, the effect of all those parameters and just relate that to the thing about the interface that's also important to the strength of the bond. That's not easy.

Speaker not identified:

Jack, I agree with you, when we talk about strength, we will have one state of stress in interlayer, you have a complex state of stress and therefore you have a kind of a ....(portion inaudible).... if you want to define it that way in which when we teach our undergraduates here we reduce it to evaluating the yield point or so. I look at it but this is my personal view, I look at it as well, that gives me a way to evaluate the ability of the composite structures to resist failure and they have a load situation. If I change the load situation which is going to change the stresses at the interlayers, the whole scene might change. But at least I have one parameter that I can correlate with something.

Speaker not identified:

I've just got a couple of questions. Yoseph, on the C-scans that you showed, what was the Y scaling or the amplitude values, was it RMS, that's what it was?

Yoseph Bar-Cohen:

That will help a little bit to imagine the process that is important for the purpose of inspecting with leaky Lamb waves. The test setup as you recall is sending a wave onto a bonded system which is really not important. What we have here cause we are looking at the thing that comes back. The transducer is set here and what we send is basically tone burst, in this case which looks like something like this. It's a given frequency which we determine ahead of time and there's a way to find it out basically doing what I showed earlier, find where those minima are. Once we set it up we know we are going to work on individual frequencies, whatever it is. This frequency in this area we have a minima and the way it looks, when that comes back into the receiver and displayed on a scope what you see is something like this. This is no longer the characteristic of the response back and right on the side just for those of you who may not be familiar with ultrasound. The way it looks is something like this. And when you change the frequency and you change it from a leaky Lamb wave frequency, just a speckle of reflection, the reflection will look something like this. So this is a way we know that we are at the mode of leaky Lamb waves. Instead of having zero we have here things like pulses. What it is is transient effects. It takes a while from the time the wave goes into the system to establish a steady state condition. That's why we have those on the side. This is a way we recognize that we at the modes of leaky Lamb waves. So what we're dealing with is an amplitude here. What we do later is look at that in a video format, effectively just using a broadband amplifier and convert that to basically something that looks like this. Because all it is is just a conversion of RF to video display. Now in this format all we look at is a portion in a time domain. We look at the change in the amplitude. When there is unbond this is a condition, we excite plate waves and that excites a null of that zone, we differentiate between this too. We have the difference between basically unbond and bonded or anything in between is a condition which is in between.

Speaker not identified:

Is the basic difference then kind of between your technique and say like Alan's that you're looking at these certain frequency windows that you can predict, like you're using a tone burst as opposed to a pulsing method, is that the basic difference as far as what's going on?

Yoseph Bar-Cohen:

As I showed schematically at the beginning ultrasonic is a general terminology. It's just sound that is sent at a high frequency, much higher than the range of hearing, and it's a wave propagation. The wave can send into the system, whoever is using ultrasonics does the same things, send the wave with a transducer. But beyond that one that is interacting with this bonded structure, there is some difference in the way the wave is interacting and the way it is analyzed or can be interpreted. If you just send a wave in what is called pulse echo full transmission, you just send pulse in to the structure and usually the only thing you excite with that kind of a wave propagation is just a longitudinal or compression wave. However, if you excite it at an angle, that gives the room also for shear stresses to take place and plate waves are a combination of the two stresses. Therefore, it's also affected by boundary conditions of those two which are somewhat more than compression effect of boundary condition, and let me explain what I mean. In the case of compression wave, at the interface if I have water I wouldn't have free surface stresses, right? However, if I have a shear stress, the stress surfaces would be zero so they are two different things. That makes the difference clearer?

Speaker not identified:

Yes. One other question for you or Alan or John. Do you have any kind of an effect of aperture or kind of a resolution when you're using two transducers like that in a pitch catch type mode. You know when you have an image is it most sensitive right in between the transducers as far as where you're looking. Is there any type of effective resolution aperture that you can figure out?

Yoseph Bar-Cohen:

There is a limitation to the resolution because of the fact that you are not using a focused transducer which focuses on a spot but looking at larger diameter area. However, it's not that big of a deal for the bond because the kind of defects that are looked after are really relatively large, usually half an inch diameter, quarter of an inch which are large enough to be detected. So it's

really not that big of a problem. But you're right, there is a limitation of resolution.

Speaker not identified:

If you are looking for similarities between the leaky Lamb waves and the acousto-ultrasonic waves, in my view there are some similarities and the similarity is that in both cases, the beam is travelling along the bond line and that's why there is more interaction taking place with the bond microstructure, where there's porosity or disbond or inclusion or interface problems. There is more interaction taking place since the beam is travelling along the bond line and that's why in both cases, both in leaky Lamb waves and acousto-ultrasonic we see correlations between the bond strengths and whatever you call the parameter which is measured by NDE. In my view it is important in the bonded structures that to transmit somehow the beam along the bond line rather than perpendicular to the bond where the interaction is very small minimum since the bond thickness is only a few thousandths of an inch.

Speaker not identified:

I'd like to just add one additional comment to that regarding the acousto-ultrasonic technique which is that there is a kind of aperture or geometric shadowing effect depending upon the area of contact between the pulsing and receiving transducer. For example, if you're using a wheel type fixture where there is more of a line contact through the amount of rubber interface coming into contact with the panel or specimen, then you'll actually find that the very small defects that are right in between the transducers and neither transducer is directly over the defect, you'll see less of an effect on that because you can almost think of it as lines of flux, magnetic flux, that are going around the defect and so the overall geometric interaction is somewhat less. If you were to take two different transducers now that had pointed wave guides on them and where they were only making point contact with the surface of the panel you would see proportionately greater interaction because of the geometric shadowing effect of the defect in between the two transducers and now it's not so sensitive as to the

position of the transducers relative to the defect. In fact I can think of one application which was a through transmission one on a bond line on a plastic bonded material where we were able to resolve defects down in the size of around ten thousandths diameter based upon using a pointed wave guide type of effect. That certainly would not have been possible with something that had a broader surface contact.

Speaker not identified:

Because there are so many different techniques I think maybe some of the people are confused about differences between some of them. First of all I want to comment about acousto-ultrasonics and some kinds of guided waves which propagate. I believe in acousto-ultrasonics, it's some kind of black box of acoustics, you send sharp pulse and have bunch of modes which not clear what it is, some of them sensitive to the bond line, some of them not. If you're using specific guided modes we can presumably select optimum mode trying to evaluate this bond line. But if we have a very complicated structure, it's very difficult to find specific mode which may be propagate clear and this way acousto-ultrasonic arises naturally and can be very useful. So I think if you speak only of two bonded blades it's better not to use it, but if you speak about more complicated structure, it may be very useful. My additional comment, it was some question about how you can use leaky Lamb waves or some other guided techniques, how you can localize point of measurements and because all time speak only about leaky Lamb waves is not clear. But actually you can do this using acoustic microscope which actually is the same based on the interference of deflected and leaky field so in this case you can focus the same C-scan and have resolution I believe very, very small. So for my opinion for example it's big difference between guided waves used and normal bulk wave. But you can implement guided waves very differently in different way. It's very complicated because of the understanding of acoustics in this case, but implementing different ways I believe results can be achieved by different ways sometimes getting better results than for other systems.

Yoseph Bar-Cohen:

I'd like to strengthen his point. Thank you for the comment. I agree with you. The issue of the use of plate waves or whatever waves this is just what we call acousto stress factor concept. It's really important that we know what we're doing. You're sending a wave and whatever comes and you call it strength and I don't feel good with it because I don't understand what I'm doing. Now when you don't understand it might work in the lab and it will not work in the shop and that's where we hang you. So I might agree that in cases where it is really complicated because leaky Lamb waves is the thing I'm talking about, but there are other waves. Any wave propagation where the theory behind it is good, it's important, because at least you can relate the thing you're doing with something you understand. People have been trying to call it, the concept of making correlation have been I don't know how long but many years back and at the beginning it was a result mostly because we didn't have that understanding of wave propagation. Now I think we are in the late 80's, we are doing very well I guess, we understand much more than we did before. We still didn't solve all the problems. In case where the structure is really complex, it might be no choice condition, but what alternatives. You can't test it with plate waves because the modes are not pure, I agree with you and what else do you have. So might be that is the room for methods like acousto-ultrasonic or whatever, it can be any combination of methods, but at least it works, at least you can screen 90% of the failures, that's important, at least you made some contribution. But to use that as a way to inspect materials, I'd be careful with that.

Speaker not identified:

I don't think it's appropriate to say that we could measure strength by using a stress wave factor or acousto-ultrasonic parameter or anything else. What we could do is to correlate whatever we measured by NDT method or NDE method with the strength. We just can correlate, that's all we could do, we can not measure the strength directly. What is the advantage of this acousto-ultrasonic technique is that you don't have to transmit the beam in certain direction as is the case in the leaky waves or conventional ultrasonic methods. What you do here is you just like tap the component using a piezoelectric probe at high frequency and listen to the wave propagation in other locations on the structure and the

advantage of this is that you could use it on large structures in real life practical situations. We're not talking about the laboratory environment here, we're talking about more practical situations than the conventional ultrasonic techniques can handle. Of course, conventional ultrasonic techniques are great to detect flaws disbond in cases of like C-scan. We're not talking about replacing or competing with the conventional ultrasonic technique. This is just another technique, maybe a complimentary technique, an alternative to the conventional methods.

Speaker not identified:

I'd like to make one additional comment on that also. I'll have to borrow a quotation from Dr. Powe of Cornell when confronted some years ago with the fact that not enough was known about acoustic emission to draw conclusions about it's utility and he said that "God forbid that we stop eating because we don't understand the digestive process." I think it's an appropriate comment here that even though we don't understand all the physics associated with acousto-ultrasonic wave propagation we are in fact beginning to fill in those voids of understanding and we do recognize now some particular wave mode types that are travelling in plate type materials but I would also dispute that in fact you can not use it on single bond lines, some of the work that I showed and some of the work that has been reported earlier including a presentation given yesterday by Dr. Fahr shows very clearly that you can use it in single bond line type applications and you can draw a correlation with strength. But again it's an empirical process, we don't propose from first principles or theory that you can be able to take the acousto-ultrasonic response and predict the strength without having done the physical correlation and testing. It's a limitation but let's face it, whatever alternatives do you have for determining bond strength in a material.

Speaker not identified:

I don't think this is the way to do it anyway.

Speaker not identified:

I would like to make one comment. Since the discussion is getting very interesting, I could not resist myself. In connection with acousto-ultrasonic technique, lot of time it is being said that it is a combination of acoustic emission and ultrasonic techniques. Originally the word acoustic emission was for the emission given out by the material which is under stress, that is something coming from the material and that was the word acoustic emission was result in the beginning. So acousto-ultrasonic technique, yes we are using two transducers, if we call one transducer ultrasonic transducer and another transducer acoustic transducer, from that point of view the name is perfect. But if somebody is saying that it is a mixture of acoustic emission, I get confused because I understand acoustic emission is coming from the material. These are the stress waves which come from the material and that's what I'd like to make clear. Thank you.

Speaker not identified:

I would like to go to another method of ultrasound that has not been discussed here and has not caught attention of anyone at this Workshop yet. This is called EMAT ultrasound. Most of the experiments that one can do to detect unbonding or debonding on metal and rubber or something else could be done very well with EMAT ultrasound technique. At T.D. Williamson in Tulsa, we are trying to detect loose coating or debonding of cold tar on five steel pipes using this EMAT and exciting Lamb waves and we see that the loose bonding, you could not miss it with this technique. The experiments that Bar-Cohen had done for example using a complicated method could be done very well with EMAT which is a non-contact method. So I would like to bring your attention to this type of ultrasound generation and detection which is called EMAT.

Yoseph Bar-Cohen:

Well somehow I think we have concentrated mostly about methods, which one is better than the other and it sounds like we're trying to market, one method better than the other. I think the major issue is we have many methods and I

don't want people to be confused, we have many methods of finding defects, we have excellent tools now. What we really need is somehow now to get into the complex issue of how to deal with the problem now that we have good tools. The problem is how to deal with the interfaces and we have to find a way to define or design experiments where we can narrow down the number of variables and if we can do that, we can step into that capability, otherwise we will be in the same condition having rather new or more methods of finding defects.

Speaker not identified:

I'd like to leave you with some thoughts. One of them is you might be getting impressions from the presentations today that we are always after bonds with a very high strength. That is not the case all the time. One system, for example, is bullet resistant glass in which the bullet resistant glass is glass plates with a plastic in between bonded together. You want the inner layers to have poor adhesion and the outer layers to have very high adhesion so there's an optimum there somewhere. That is for the purpose of absorbing the kinetic energy of the bullet in inner layers by delamination. So how do you measure, do you really want to control the level of adhesion and let me call it strength with permission of Jack Duke there. So the things can get complex there even the way they test systems like windshields is rather different than just peeling two lap joints. You'd be surprised the level of subjective from one side yet the level of accuracy that I see operators testing these type of systems. They are very, very consistent but no nondestructive testing yet has been proven except acousto-ultrasound, that I know because I have been doing that.

Paul Kenny:

OK. I guess we can leave on that note and we can at 6:30 reconvene for further discussion in the Lime Room.

Yoseph Bar-Cohen
Douglas Aircraft Company
Long Beach, California

Ajit K. Mal
University of California
Los Angeles, California

ULTRASONIC NDE OF BONDED STRUCTURES

As you can see, I'm going to talk about NDE of bonding. Everyone was talking about this today, but I'll try to look at it from my point of view and it might be shared by others who talked today and talk tomorrow. What's the background? (Figure 1) Conventional NDE in general detects unbond mostly and basically can't characterize adhesive properties and some have been familiar with methods of determining maybe elastic properties of the adhesive, the thickness, things that might be associated with the quality of the bond but basically that's what we have. I'll show some of those in my talk and see what they do and see how they do it. But the sensitivity of those methods and specifically I'm going to talk about ultrasonics, are basically affected by the edge effects which is one of the most important things in adhesive bonding, the edge. If we have a strong attenuation either in the adhesive or in the bulk system we have a problem. Other areas where ultrasonics has a problem is high mismatch at the interface and that's the issue that I talked about yesterday about the steel to rubber. I'll mention that today too and of course if the adherend has a very low acoustic impedance, then we do have a problem again. One example is the steel rubber and the other one may be the foam adhesive that someone talked about.

Now the thing is the adhesive properties or the strength of how the adhesive is actually transferring the stresses between the members of components of the system is depending on the interface itself and that's the thing we don't have right now. We don't have that tool that tells us how that interface is holding (note Figure 2). If it is almost what is called kissing adhesive or all the other ways of being in intimate contact, we have an imitation there and the question is what can we do in this area.

As far as ultrasonics, there are quite a few methods (Figure 3) that also were mentioned by Glenn Light. I'm not trying to overlap what he was saying but

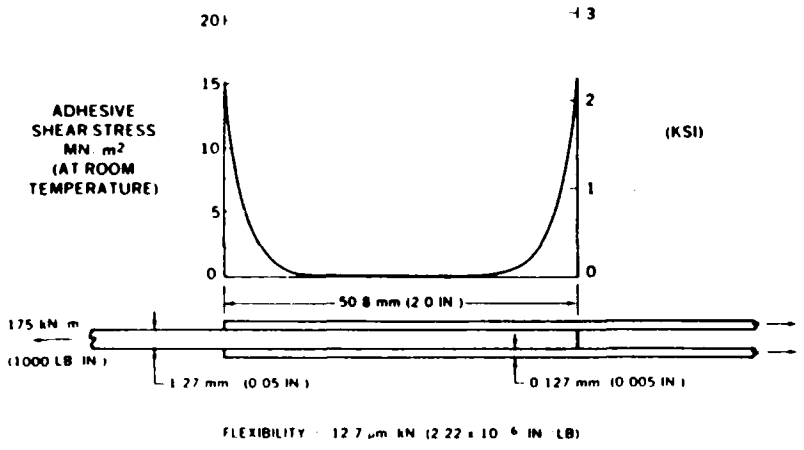
BACKGROUND

* CONVENTIONAL NDE - DETECTS UNBONDS AND CHARACTERIZES ADHESIVE PROPERTIES (THICKNESS, ETC.)

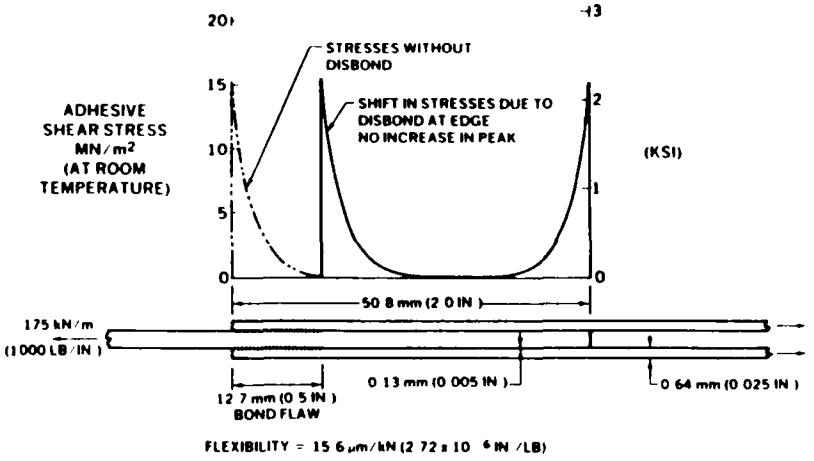
* REDUCED SENSITIVITY DUE TO:
  - EDGE EFFECTS
  - STRONG ATTENUATION IN THE ADHESIVE SYSTEM
  - HIGH MISMATCH AT AN INTERFACE
  - LOW ACOUSTIC IMPEDANCE OF BACK ADHEREND

* INTERFACE PROPERTIES DETERMINE THE STRENGTH OF BONDING.
  - CANNOT BE DETERMINED BY CONVENTIONAL NDE METHODS.

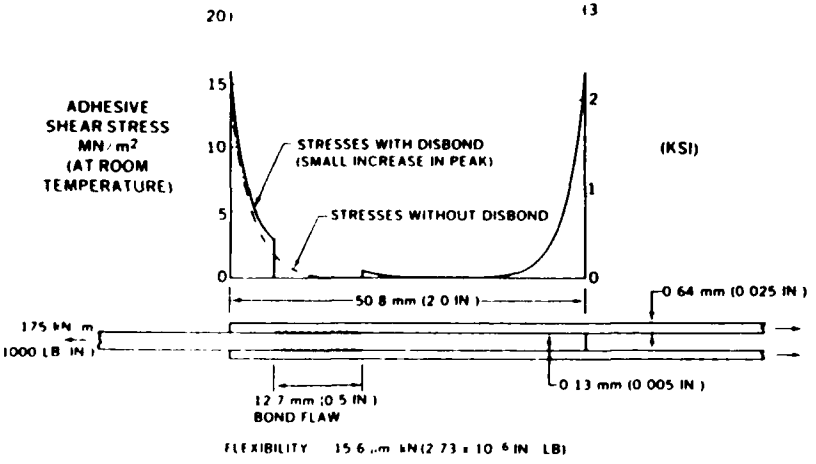
Figure 1



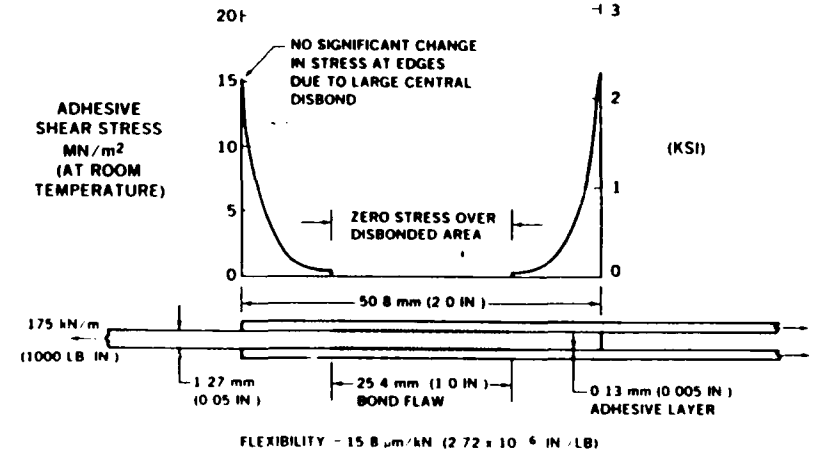
ADHESIVE SHEAR STRESSES IN BONDED JOINTS



ADHESIVE STRESSES IN FLAWED BONDED JOINTS



ADHESIVE STRESSES IN FLAWED BONDED JOINTS



ADHESIVE STRESSES IN FLAWED BONDED JOINTS

Figure 2

ULTRASONIC NDE METHODS

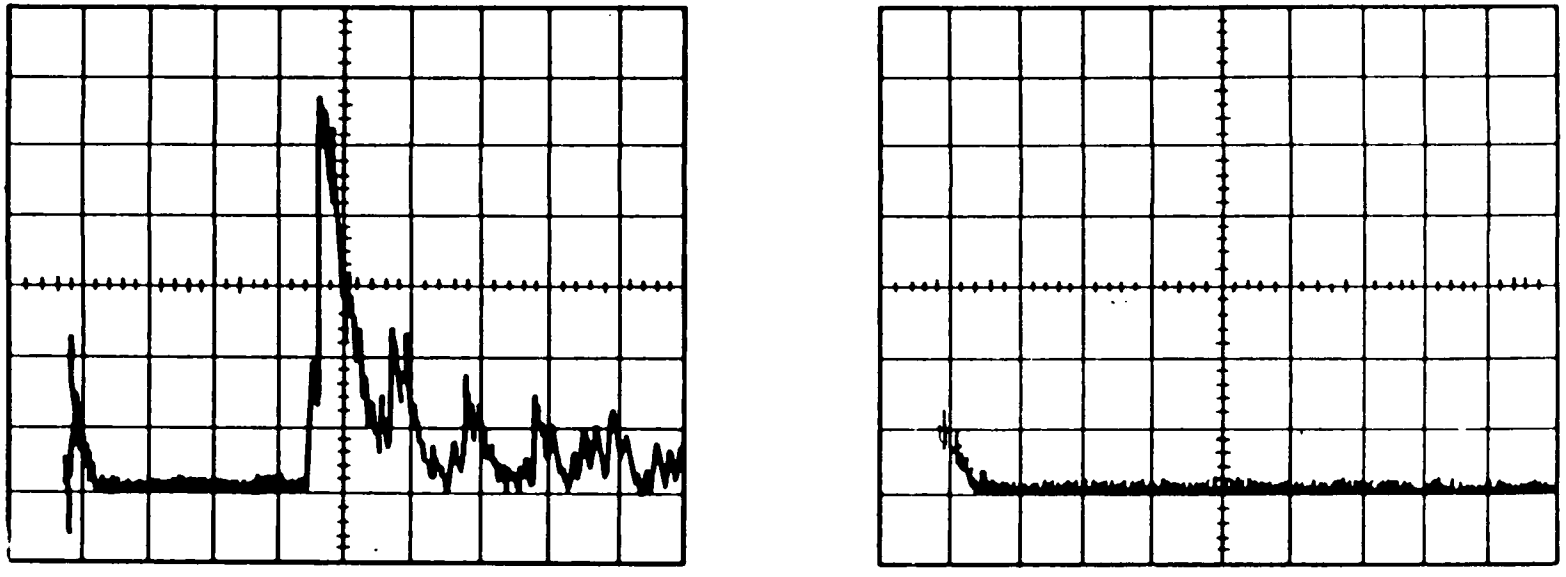
* RESONANCE
* PULSE-ECHO
* THROUGHT-TRANSMISSION
* SPECTROSCOPY
* LEAKY LAMB WAVES (LLW)

Figure 3

basically as mentioned here, we have traditionally had those, at least the four top methods, be known and now recently we have seen more of the leaky Lamb wave and I'll mention that too. Each one of those methods have been able to identify unbond and let's hear a bit how they do it but the way, all ultrasonic methods somehow boils down to it's something like we have in this schematic. We have two members somehow connected to each other through an adhesive bond and the waves get through either in an oblique angle in some kind of a way and we get all kind of reflections that are analyzed, it's either reflected back or at an angle or some kind of an interaction that takes place that we are analyzing that interaction. Through that interaction we're actually getting the information about what do we have inside. We are not measuring this way any strength, there's no strength involved. We are thinning a wave and we don't do any straining of the structure. The thing we are putting in is a very small amount of energy of ultrasound. There is no chance it will break the structure tested in both tests. But indirectly we are measuring things that might be associated, might be related to the ultimate thing we are looking for which is the strength. This is a simple thing, just full transmission, all structures (Figure 4). It's quick to test, you take a big part, you don't really care what it is, you send waves from one end and look at the other. If something in the middle is not bonded, the energy doesn't go through. Very simple, you don't need to be really expert just to see that this is bonded, this is unbonded. Doesn't say anything about how good is it. You can have of course stages in between which might be associated to the size of the disbond. So some people have been correlated in the past attenuation with the strength. This amplitude can disappear if we just have air trapped between the transducers that have nothing to do with the strength of the bond.

Pulse echo has also been one of the workhorses in this area (Figure 5). The advantages while comparing to the previous figure will have yes, no, or almost. If an energy goes through, there is some continuity through the media which the waves go through. In the case of pulse echo we've a little bit more complex information or signal pattern. We can get out of that information more than just saying it's unbonded, it's bonded. Of course there's a limit to what we can do with this information. This figure shows an example of one of the samples that has been bonded and tested. In this case, A (of Figure 5) is a reflection from the top surface, C is a reflection from the bottom of the adhesive, in this case

THROUGH TRANSMISSION RESPONSE OF A GRAPHITE/EPOXY HONEYCOMB SANDWICH SPECIMEN

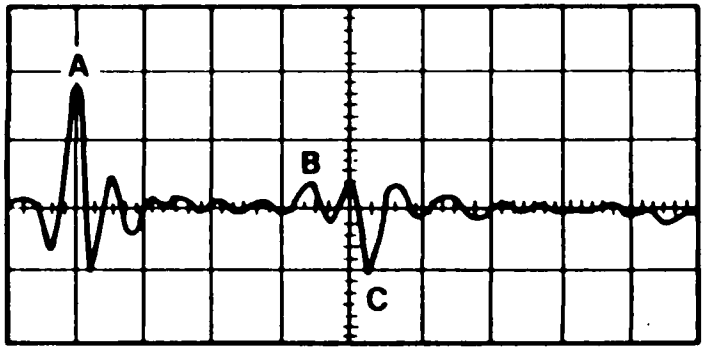


A. BONDED

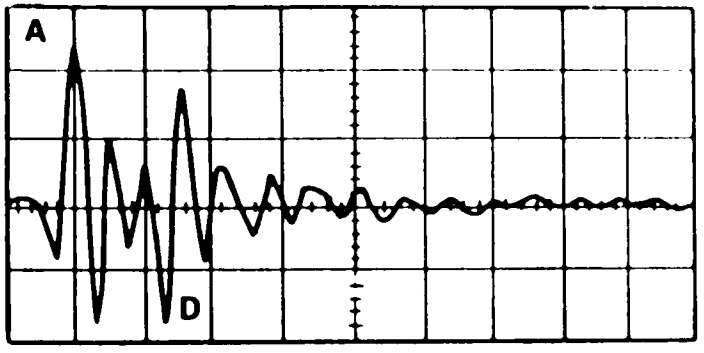
B. UNBONDED

Figure 4

PULSE ECHO FROM SPECIMENS OF GRAPHITE-EPOXY [0, 90]$_{2S}$ AND GLASS-EPOXY [0]/ADHESIVE FM73/ALUMINUM HONEYCOMB



BONDED SAMPLE



DELAMINATION BETWEEN 4th AND 5th LAYERS OF THE GRAPHITE/EPOXY SKIN

UNBOND BETWEEN THE GLASS/EPOXY AND THE ADHESIVE LAYER

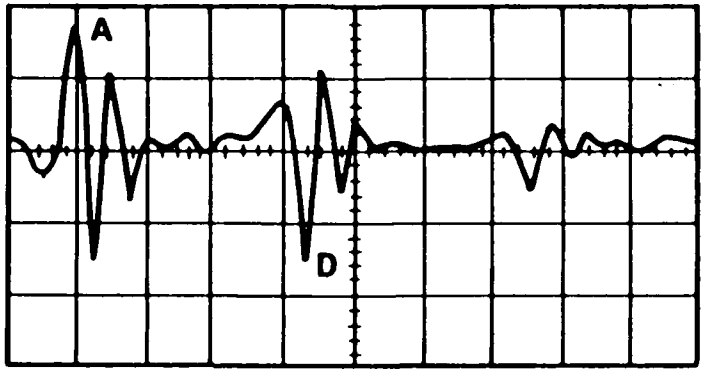


Figure 5

it's a honeycomb structure so we do get significant reflection from the bottom of the adhesive and there was a layer of graphite epoxy there. So we do have information here about the structure and this is supposedly a good looking part or a sound part. If we have disbond or delamination, those are identified for the pattern that we get. In this case we can also tell how deep the delamination is or the fact that we have a disbond between that fiberglass and the bottom adhesive. These have been a change of phase between this one and this one. But beyond that information of saying there is unbond or delamination, there's nothing here that says anything about the quality. If there's anything intermediate it's how to tell what is it.

Another way of doing it is for resonant testing, there's an instrument known as Bondascope (Figure 6). There what we do is measure the loading characteristic of the transducer and people have mentioned that today too. We can find if the structure is bonded or unbonded, really there is just difference between the two, we can just identify the fact that there is unbond. This same method has been used with an instrument that was developed by Fokker for determining strength. For many years, at least through the 60's and 70's, that was a popular thing to use to determine the strength. The idea was that there is some remission between the thickness of the adhesive and the shear strength which was measured through lap shear. Actually there is a relation here is with the thickness of the adhesive because as you can see if there is no porosity in that adhesive there is barely any effect. Even though the thickness is changing, the shear strength is really not affected that much. It's almost within the ball figure here. However if there's a lot of porosity in the adhesive there is something to be able to relate to. So really you have to know the system that you're dealing with and to know that you have porosity there. So how would you know, you're putting a transducer, you don't know what you have in there to determine if it's strong or weak because you're actually measuring something that is associated with the adhesive thickness and you're trying to correlate that with the shear strength. An example of the thing that was correlated (Figures 7 & 8), but just so you can get the idea. There is some indication on the screen which is the change in the resonance frequency of the probe and that somehow supposedly can be correlated to the strength of the adhesive but as I said what really the transducer is sensing the change in the thickness of the adhesive and the fact that that change is not necessarily indicating the change in the strength because the previous curve

A DISPLAY OF THE TRANSDUCER IMPEDANCE FROM THE BONDASCOPE 2100

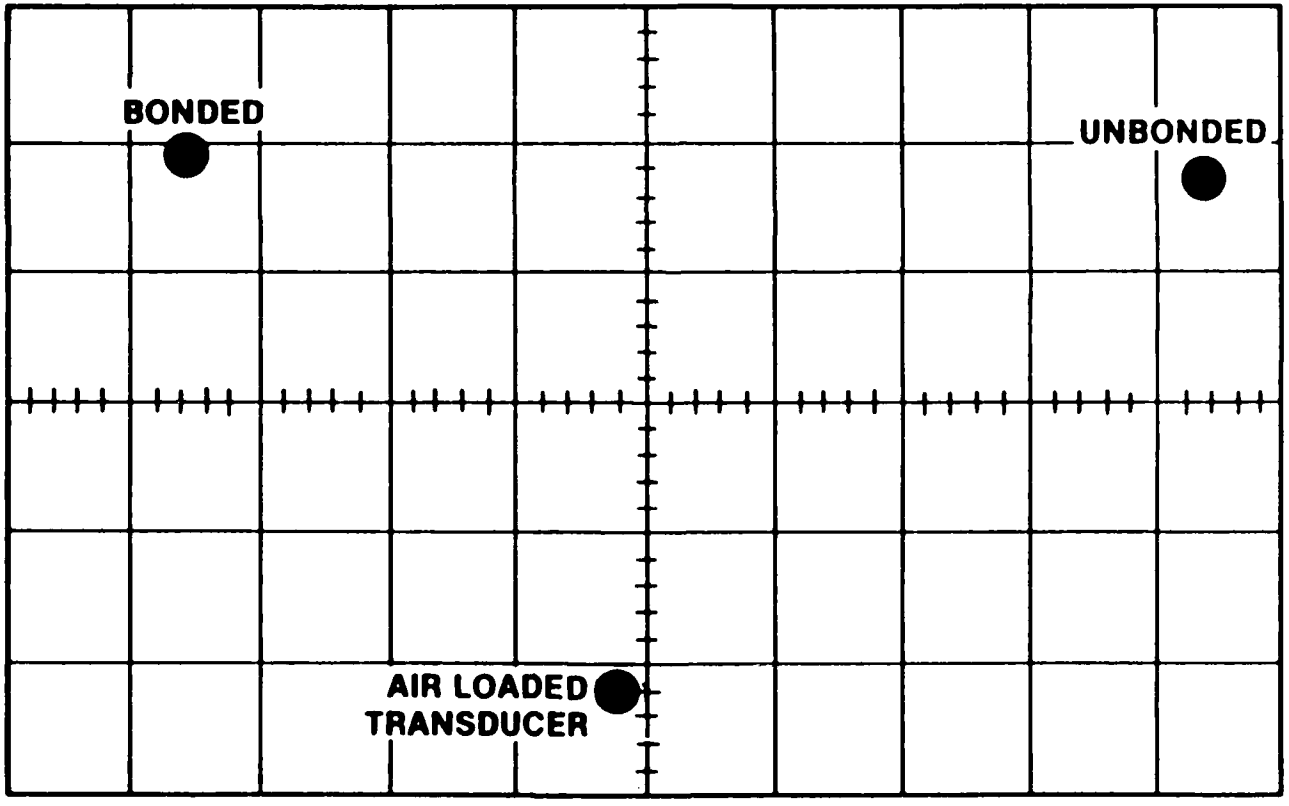
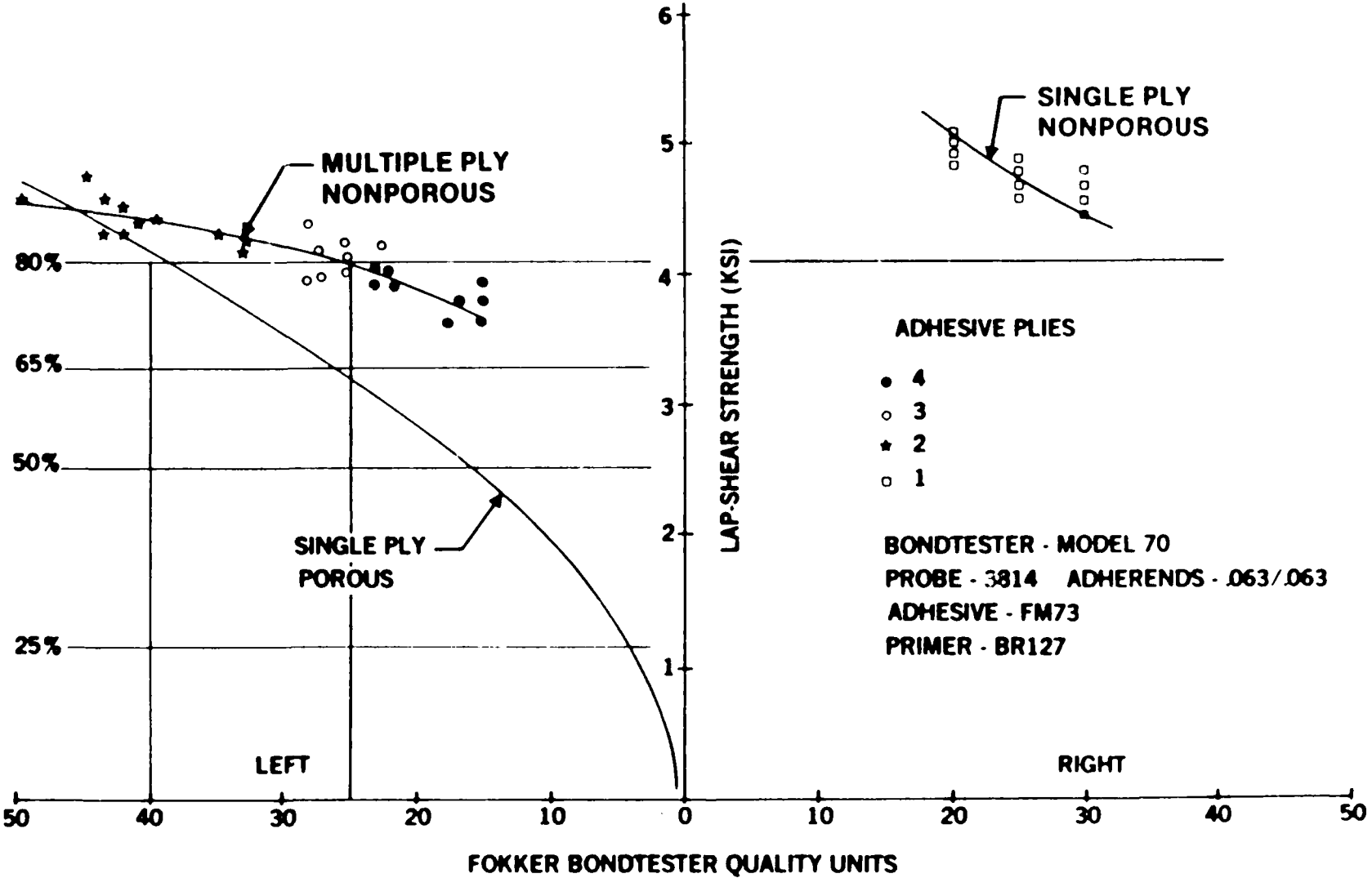


Figure 6

LAP-SHEAR STRENGTH VERSUS FOKKER BONDTESTER "QUALITY" UNITS



*BASED ON HAGEMAIER, 1977

Figure 7

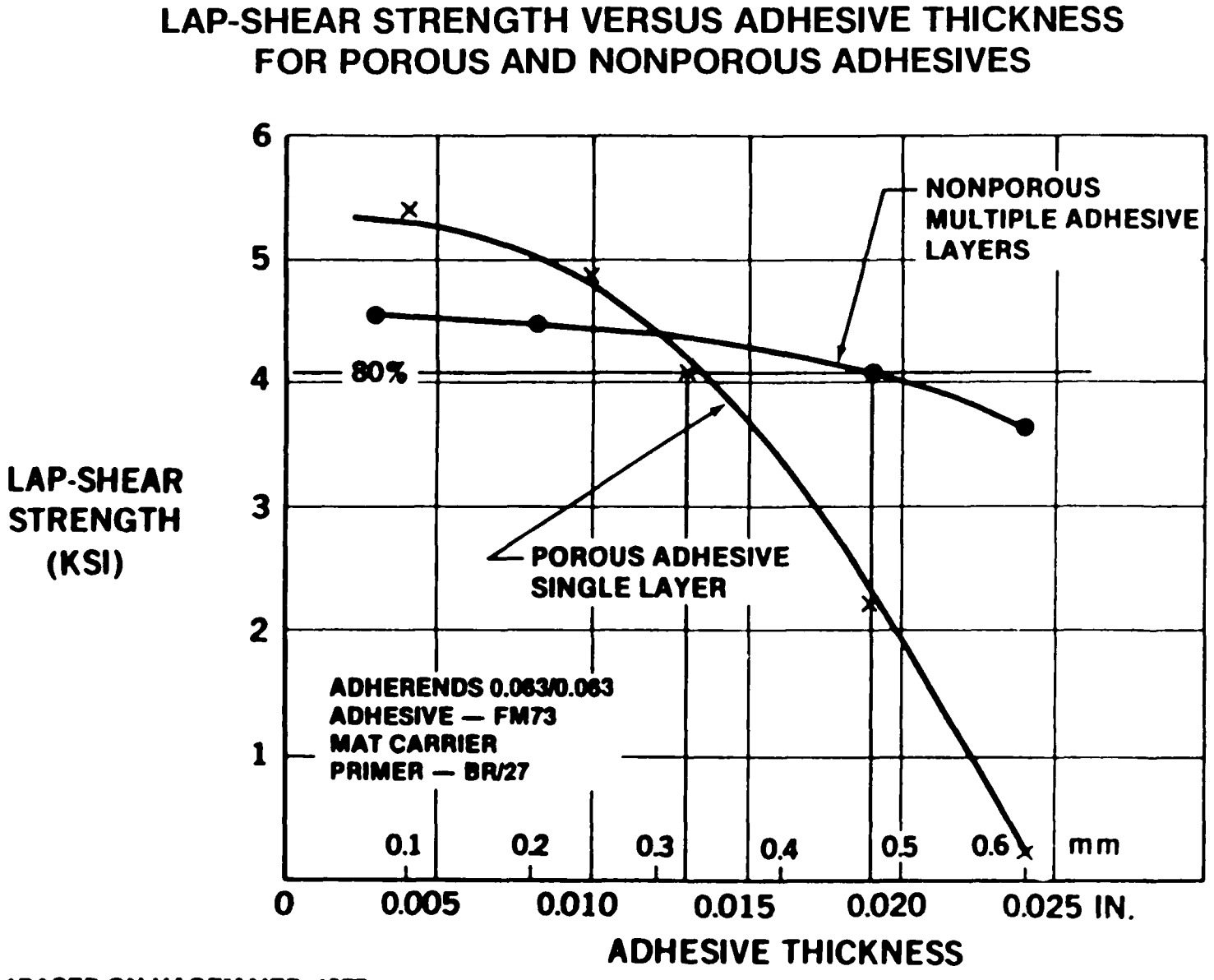

LAP-SHEAR STRENGTH VERSUS ADHESIVE THICKNESS
FOR POROUS AND NONPOROUS ADHESIVES
LAP-SHEAR
STRENGTH
(KSI)
6
5
4
3
2
1
80%
NONPOROUS
MULTIPLE ADHESIVE
LAYERS
POROUS ADHESIVE
SINGLE LAYER
ADHERENDS 0.063/0.063
ADHESIVE — FM73
MAT CARRIER
PRIMER — BR/27
0.1
0.2
0.3
0.4
0.5
0.6
mm
0
0.005
0.010
0.015
0.020
0.025 IN.
ADHESIVE THICKNESS
*BASED ON HAGEMAIER, 1977

Figure 8

showed that if there is porosity there for the same thickness you get different strengths.

Another method that seems to be catching up again is called ultrasonic spectroscopy. The advantage there is that we get more parameters about the interaction with the adhesive. The problem with the previous thing that we saw is all we have is one parameter (Figure 9). In one case it's a dot moving on the screen reflecting relation to the impedance properties of the transducer. In the other case it's a resonance frequency of the transducer or amplitude change but that's only one parameter. You know how many variables there are in that system of adhesive bonding? It's an unbelievable number, there are so many variables. Even the surface roughness can affect that. So trying to correlate that with the strength is really very difficult because the strength itself is undefined, that well at least. So what we have here (Figure 10), think that we have determined as far as what will be the effect or the spectral response of a system with water, aluminum, epoxy, again aluminum and at the back of course we have water (Figure 11). So we have a bonded system and this is the kind of characteristic response we get; however, it is unbonded. We get different characteristics and if we adjust the plate with air at the back we get different characteristics so through that characteristic we can tell something about the unbond. But still that has nothing in it to reveal the strength of the bond. We assume here ideal conditions. We have one layer called the adhesive, the other layer is called aluminum, maybe two layers just bonded together and if they are bonded perfectly we have one characteristic response. If they are not bonded, we have another.

We have an example of the comparison between a few experiments so basically we are able to prove that if everything is right we can predict to be heavier. Here is just one thing that also I would like to show. It's important also to know the thickness of the adhesive. It can't be too thick in relation to the wave that we are using otherwise we won't get any transmission through. The thicker it is the less transmission goes through the adhesive. So it's important to use high frequencies. But in most cases we don't have any problem because we're using high enough frequency that the wave length is much bigger than the thickness of the adhesive.

This graph was taken from work by Harold Smith from Douglas, it shows how much we have to be concerned about defects. As Glenn Light showed today and a

PULSE ECHO FROM A THIN ALUMINUM PLATE

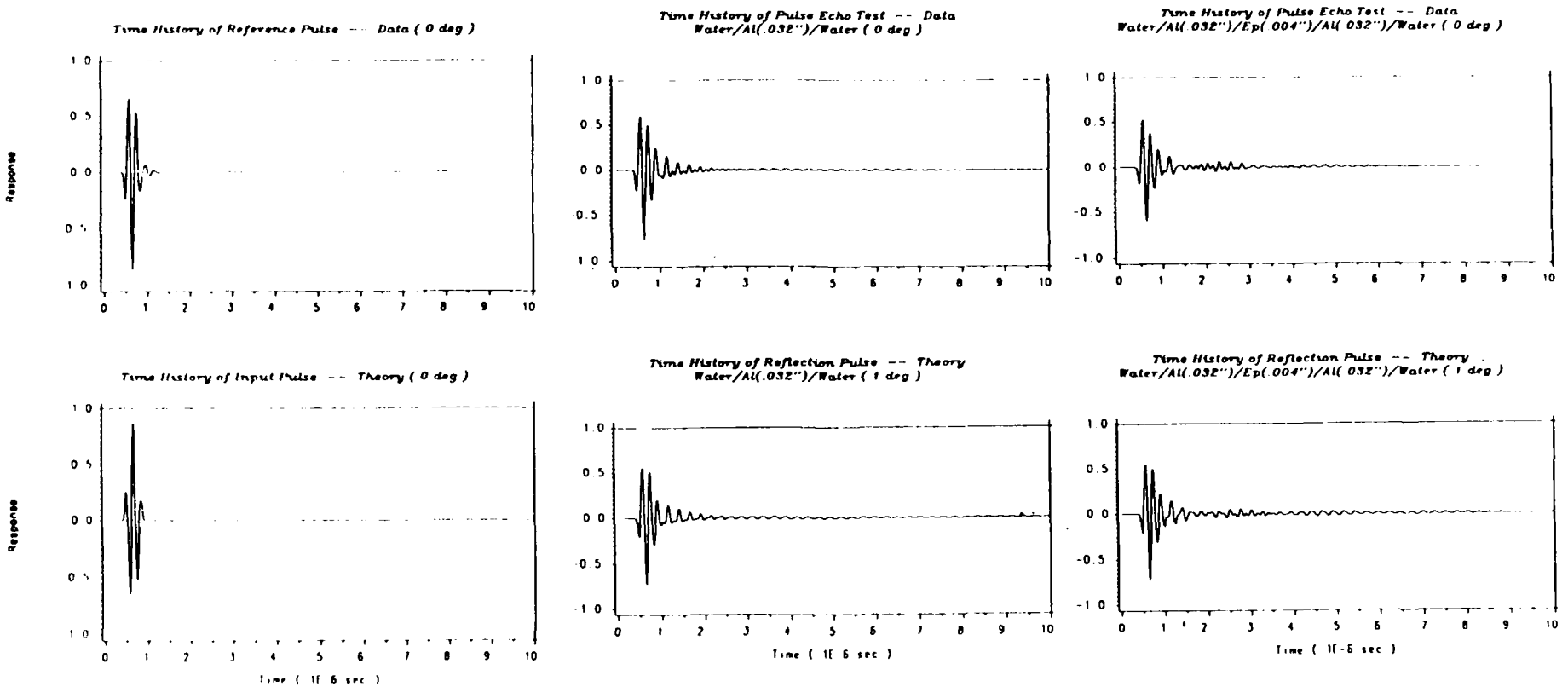
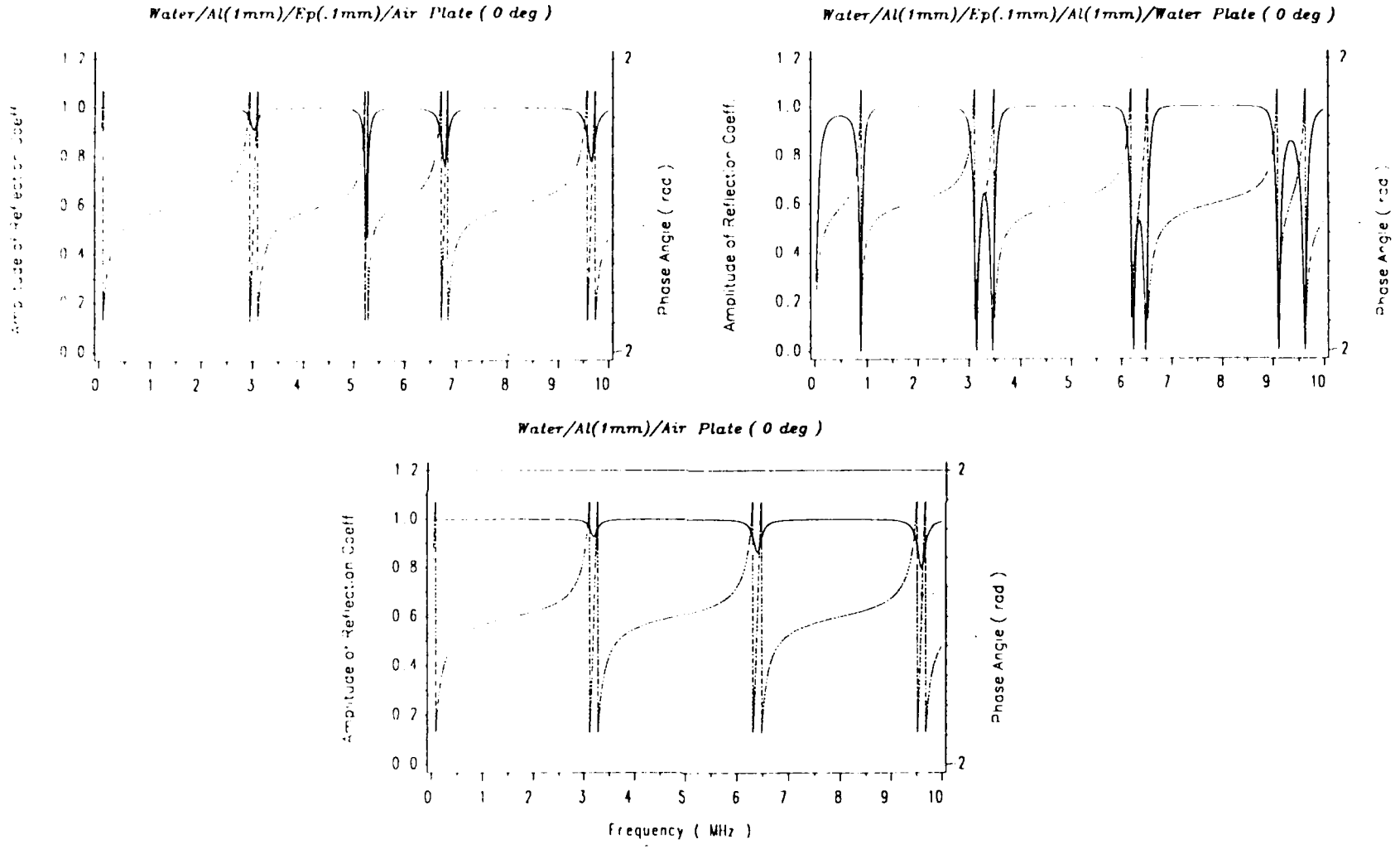


Figure 9

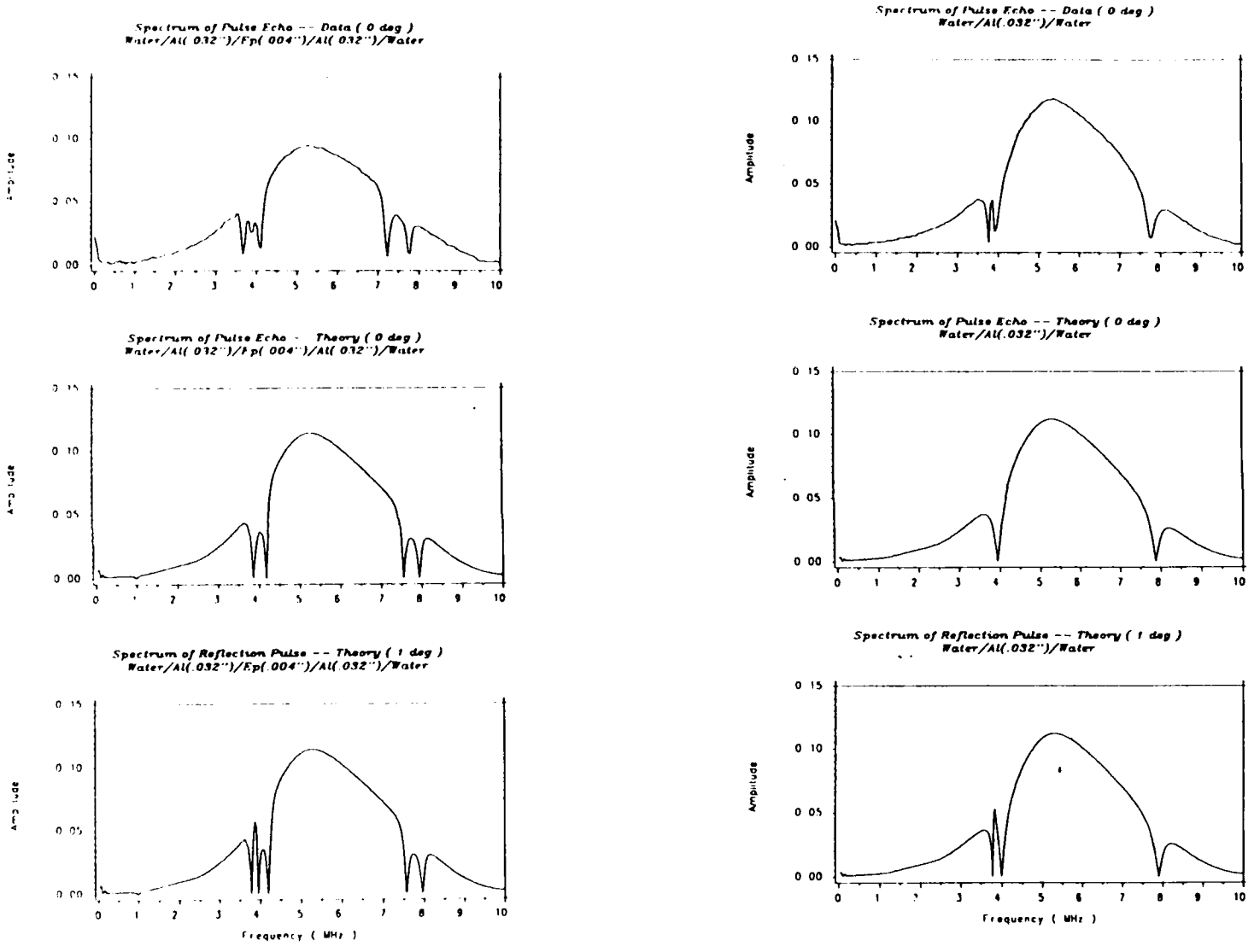
AMPLITUDE SPECTRA OF THE CALCULATED REFLECTION



NOTE: Amplitude spectra of the calculated reflection from a perfectly bonded aluminum plate (top) a plate with complete debonding at the lower epoxy-aluminum interface (middle) or at the upper interface (bottom).

Figure 10

AMPLITUDE SPECTRA OF THE PULSE ECHO DATA



NOTE: Amplitude spectra of the pulse echo data shown in Figure 9.

Figure 11

few others, there's really a long arsenal of methods of detecting unbond. What we don't have is basically one major thing. We do not have a way to identify or relate to the interface itself. The surface that I'm trying to show is showing really what the effect of the unbond. We have a layup of lap shear and what we can see is if this is loaded, this is basically the stress distribution. Mostly we have high stresses near the edges and that dropped very quickly in few thousands of an inch here to really almost zero. Most of the stress which was mentioned earlier too is concentrating at the edges. Now what really happens, if we have a defect, here's an example of a defect, I think it's almost one inch or something. See what happened, really nothing. The stress finds it's way around the defect and ignores the defect. You can just see it, even if it's near the edge. The stresses ignore the defect and basically it starts from that, of course there is a high concentration here but the fact is we do have that three distribution of stresses. This is really critical because the fact that we have a high stress is that the unbond will create a zipper effect. However here is another example. We took an unbond, very large, almost from this point to the other point which is fairly large, but the fact is in this area we don't have stress to worry about. Even if we have to develop the best method in the world with all the nice colors and everything, so what, no one cares, it's really not important. So we have to know when it's important. It's important near the edges or making sure that these stresses do transfer. They would be transferred only if the interface is good because the adhesive itself is going to be good plus/minus some degree of variance. But even if it was not cured well, sooner or later in service it will cure itself. Those are polymers, they tend to cure in-service too. But the key here is if you didn't do a good job and follow the interface there's nothing you can save the structure from failing later.

Back to the method called leaky Lamb waves, I mentioned it earlier yesterday. I'll talked about it today but here I would like to show in perspective how exactly the thing is working (Figures 12 & 14). This method is just an oblique incident method where you send the wave in an angle into the structure. At certain frequencies, instead of just being reflected just as a specular reflection, what happens is we excite plate waves in the structure. Those plate waves leak energy back. The leaking energy interferes with what is the specular reflection and we get this kind of pattern of two lobes with an null between them because of destructive interference (Figure 13).

SCHEMATIC DIAGRAM OF THE LEAKY LAMB WAVE (LLW) FIELD

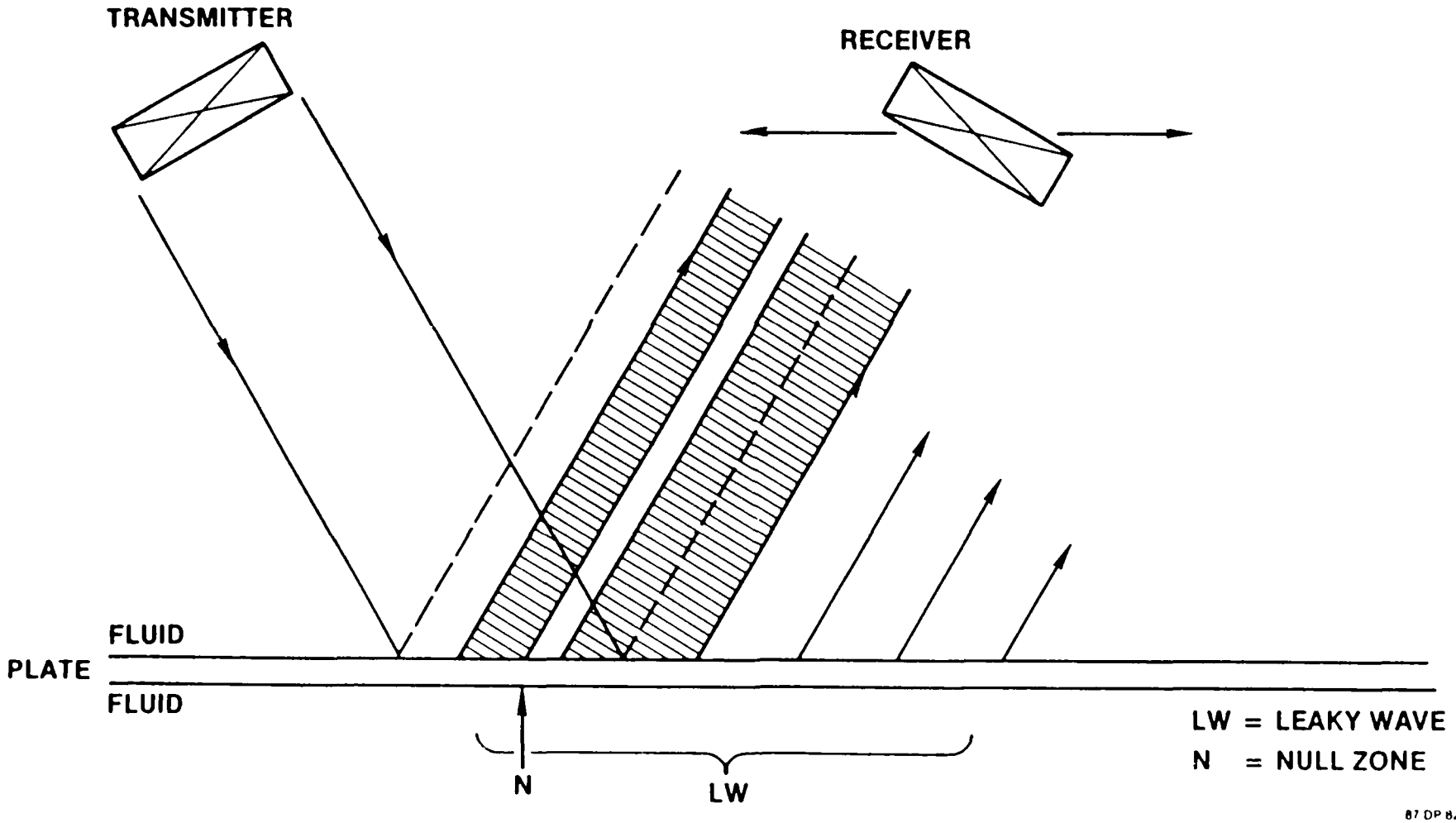


Figure 12

MEASURED AND CALCULATED LLW SPECTRA FROM A UNIFORM AND BONDED ALUMINUM PLATE

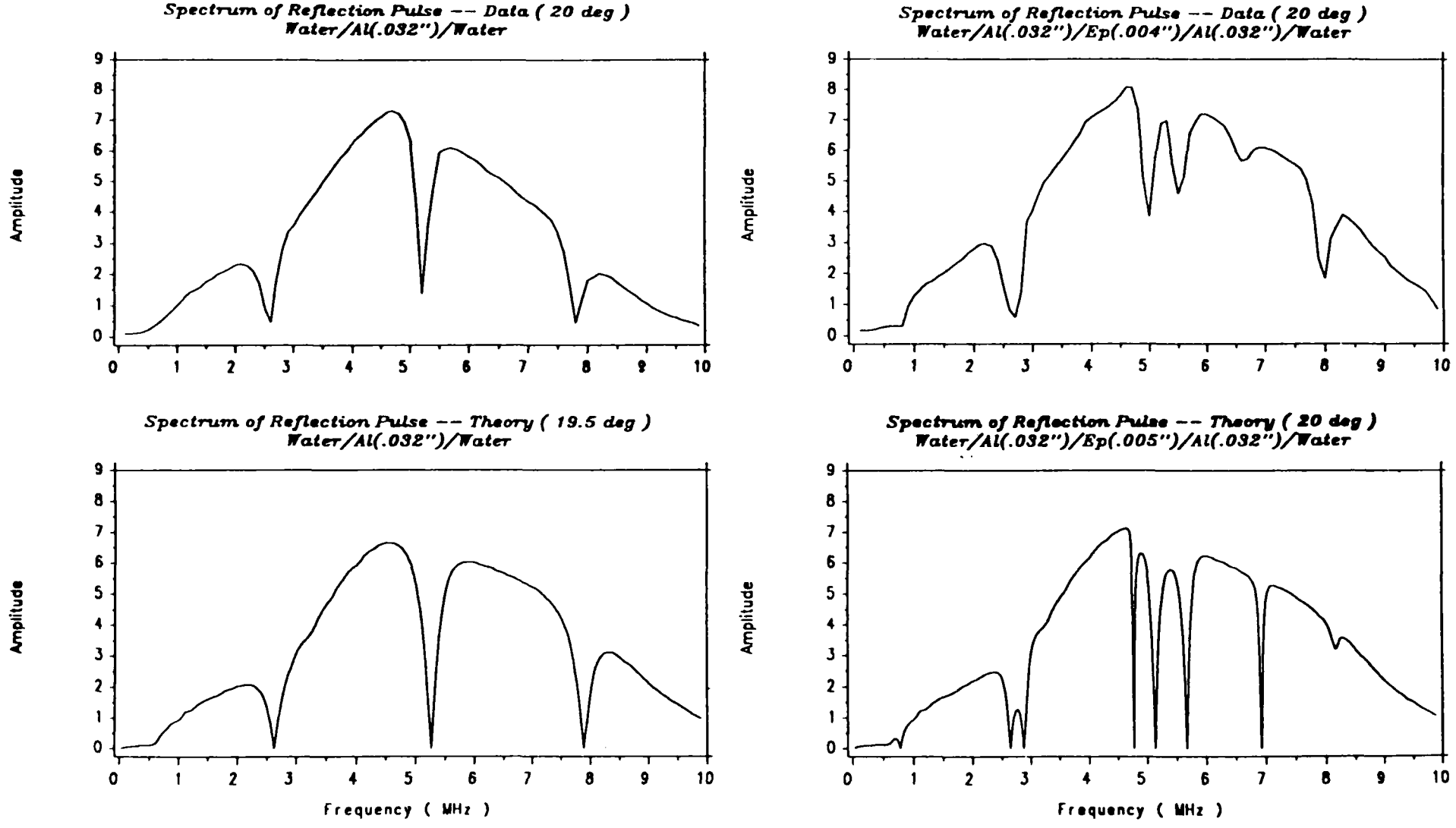


Figure 13

I think we have a Schlieren picture (Figure 14), I showed that yesterday too for those who haven't seen it. The wave before incident with pulse Schlieren and you can do fancy things, you can see the wave before it hit, after it hit, so what happened before, a nice looking burst of wave, and this is what happened afterward. If you look carefully, you can see that there is a phase difference because this dark line goes exactly into white line which means there is a phase difference between this wave mode and this one. There is a destructive interference as I said in between. So if we put a transducer somewhere here in the receiving area, then we have a very sensitive tool because destructive interference is a very sensitive parameter in physics. That's somewhat different than just putting a transducer somewhere here and looking for leakage of waves. Because even though you're seeing a leaky wave it's still not taking advantage of the phenomena. It is really not necessary just to say leaky Lamb waves because other modes will leak as well at different frequencies so we might use leaky guided waves because any guided wave that leaks back to the water will create this kind of behavior and will be allowing us to sense the properties of the material. Now the beauty of this phenomena is the fact that these are really sensitive to the properties of the bulk as well as the interface. Changing the boundary conditions can be sensed here very easily. Let's see some things about it.

This (Figure not furnished) came from work I did earlier with Dr. Chimenti from Wright-Patterson where I embedded unbonds, full simulation of course, taping Teflon at the back. In this case what we're really exciting or generating is plate conditions in this area which is not bonded. So all those areas which were not bonded were picked up with the phenomena. I connected a Siskel set-up with a leaky Lamb wave set-up. So this is the kind of thing we got. We're dealing here with a method of detection of unbond at this point. Someone might say, OK, no big deal but for this case it is because the honeycomb was Nomex and it's really difficult to detect. It has a low impedance and it's really tough to detect it when it's bonded to a composite.

This wave method somehow is used in experiment. What we do is sweep the frequencies and we can find each time we get the minima there is that phenomena of leaky Lamb waves where if we study what happened at these individual frequencies we can find changes in the material. Something that was taken from

PULSED SCHLIEREN IMAGE OF A LLW MODE FOR A TONE-BURST SIGNAL BEFORE AND AFTER IMPINGING ON A GLASS-EPOXY SAMPLE [13]

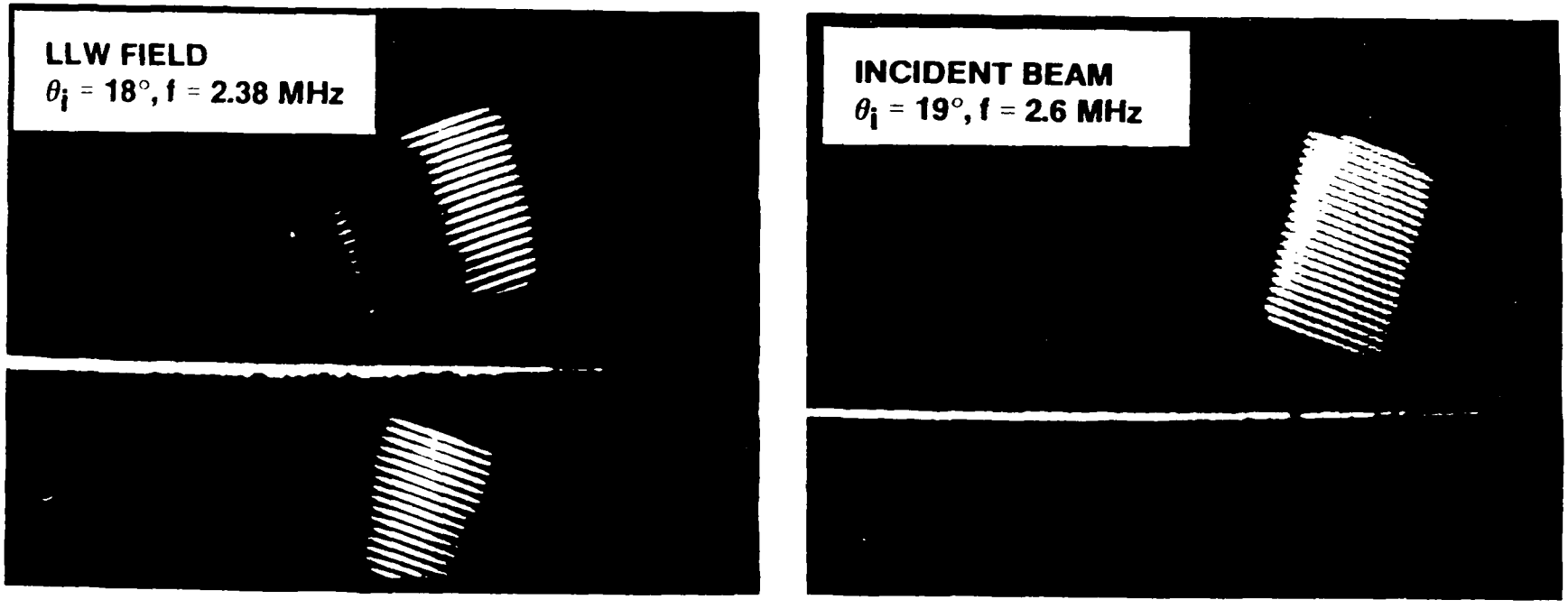


Figure 14

yesterday and Dr. Ting also showed that but this is in color, it looked nicer so I'll repeat it anyway, I hope you don't mind. This is what happened when you use pulse echo in a bond between steel and rubber. Because of the fact that there is a big mismatch between the steel and the rubber and the fact that rubber has properties very close to water, it's hard to detect unbond in this case. In this case the unbond was supposed to be in this region. It's hard to see it, you can see that even the difference in colors between the red and the green in this scale is very small, very tiny difference. However, when we use the leaky Lamb wave basically that's what we're seeing. The unbond was picked up clearly and the bonded area looked green or blue. Now I'd like to make a point about this. This area, I also mentioned that yesterday and that's important to this talk, this area was prepared by the removing or masking the adhesive. We did not apply any adhesive on the steel. We made sure there would be no adhesive prior to applying the rubber. Now the rubber itself is Neoprene. Before it is bonded or before it is cured it is very tacky, it's something where if you put your finger, it sticks to it but you don't need to scrape it from your finger, you can remove it just as well. So it tends to adhere, but weakly. We have some evidence that there's something in here with this frequency. Here we use one of the frequencies of the mode, I don't remember the number. However, look what may happen when we looked at different frequencies. Now we're looking at a different mode of the same phenomena using the same exact setup except that we looked at the different frequencies. Suddenly many things have been hidden (playing around) the area which we called weak or low strength is shown here. The unbonded steel very clearly is shown however this is an area which is very interesting. Of course we're all seeing things that we don't have an explanation yet but we are relating it to the fact that we are dealing with anisotropic, the steel is anisotropic, it has grain boundaries, all the things taking place here that we need to take them into consideration. So this is part of a different work then, I talked about that yesterday. But for this purpose, we try to see if we can somehow have a new way or new tool here that is picking up weakness and we know it is weakness, it is not strong. To separate the unbond we had to stick a spatula on the side. All it took was a spatula, that is a very low stress needed to push by hand a spatula and separate the rubber from the steel. It is not that strong in this area. So to separate this weak area we have been able to do it by hand. You can not do it in this area. So we are able to see weakness. So we have here a feasibility of a new approach that needs to be looked at carefully.

It might be just a coincidence, but at least it deserves attention. Here we try to see if we can somehow define a parameter that can be associated somehow to the quality of the adhesive interface and that can also be picked up by ultrasound. Something that we can put into a model, I don't think we can put a strength parameter, I can put A = strength into any of the models we can deal with, because it is not a physical thing that we can associate with. But if we put somehow a parameter, a physical parameter, then we can correlate that somehow with an experiment. Later we'll worry about how to relate that to the meaning of strength somehow. So what we did is the thing I mentioned in the morning in one of my comments. We try to think of the idea of the weakness of an interface, assuming this interface is a layer, it has a finite thickness after all, it's not zero thickness, it has some thickness. If we can associate that with some kind of a parameter called shear modules. Why shear? This is an intuitive feeling about the adhesive. Shear is the only thing that seemed to us to be related to that kind of a quality that needs to be in an adhesive interface. If I had two plates or layers, it doesn't matter what layer's there are, separate that apart, the layer in between is zero shear. Even if I have a fluid in there it is still zero shear which means that if I have a fluid between two layers which is exactly the same thing as kissing interface where you just have two plates together, one on top of the other and ultrasonically with just longitudinal wave it will go through and then will assume it is continuous. However, shear wave will not go through because we're dealing with zero shear. Now if we assume that the surfaces have some gripping fingers, just imagine that in a microscopic scale, then the closer those gripping surfaces are to each other, the primer and the annodize which is that interface we're talking about, the more gripping capability or the more closer they are the higher that shear strength is there. Because if it's too far, they will not transfer shear stresses but whether they are gripping together they will transfer well. So intuitively it sounds like a sound approach. We tried to test this approach and first of all we tried to do some calculation of dispersion curves in the case of unbond and bonded so we have a model right now of handling first of all the case of good bond where we assume that everything is there, in contact, very good contact.

NOTE: BEGINNING OF OTHER SIDE OF TAPE

Again just to show in general. It's really not critical to see the details of each one of those graphs, but what we have here is different orientation of the

composite and the dots on the graph are the experimental data. Now here we started to put that effect of interface quality. In this case (Figure 15), we took a system of titanium beryllium, immersed in water and we calculated the reflection coefficient and what would be the modes, those minima that will appear in this case. So we assume first of all perfect bonding, in this case it's a diffusion bonding. Well they both are in good intimate contact plus it is what is called strong bond (Figure 16). The other case where we had a very small gap between the two where we had speculated some value, the beta is our parameter. When beta is very high that means we have very good bond or that coupling factor or shear factor is the thing that we use to measure. However when beta is zero, it is completely unbonded. So here we have those three conditions. We use perfect bond, pressure bond, and complete disbond. As we can see the modes are very different and those are the things we use later if we want to somehow identify the quality of that interface. We put that in the dispersion curve, the idea is here we have those three conditions of weak bond as well as perfect bond and we get very different characteristic behavior. What we see is the certain relation between the thickness and beta. There is a region where the ability to identify the quality of bond is the highest. We have made some tests to prove this behavior in this particular system and the experimental data, unfortunately we didn't put the experimental on the theoretical, but it came very closely to matching what we have here. Of course we had a little bit of difficulty with the in-between because it's very difficult to make experimental set up which will identify that partial unbond. We had to make some speculation, but the other two cases came very close to what we predicted.

Now as far as the technology assessment (Figure 17), again conventional methods do not provide any parameter that can be related to interface property. On the other hand, leaky Lamb waves or leaky guided waves if we use water dimension, provide a great potential. Now it seemed to me that the advantage of this approach of leaky Lamb waves is the part that it provides more parameters about the test system. It's not just a single value which if you change one of the variables in this system, suddenly all your predictions are wrong. Here we're dealing with something more complex of course but that's the penalty for getting more information. The more information you get, the more independent variables you deal with, the more complex the problem becomes. But there is a benefit to it. There is a benefit of having more information that we can use to

SPECTRA OF REFLECTED ACOUSTIC WAVES FROM A WATER-LOADED BONDED SOLID

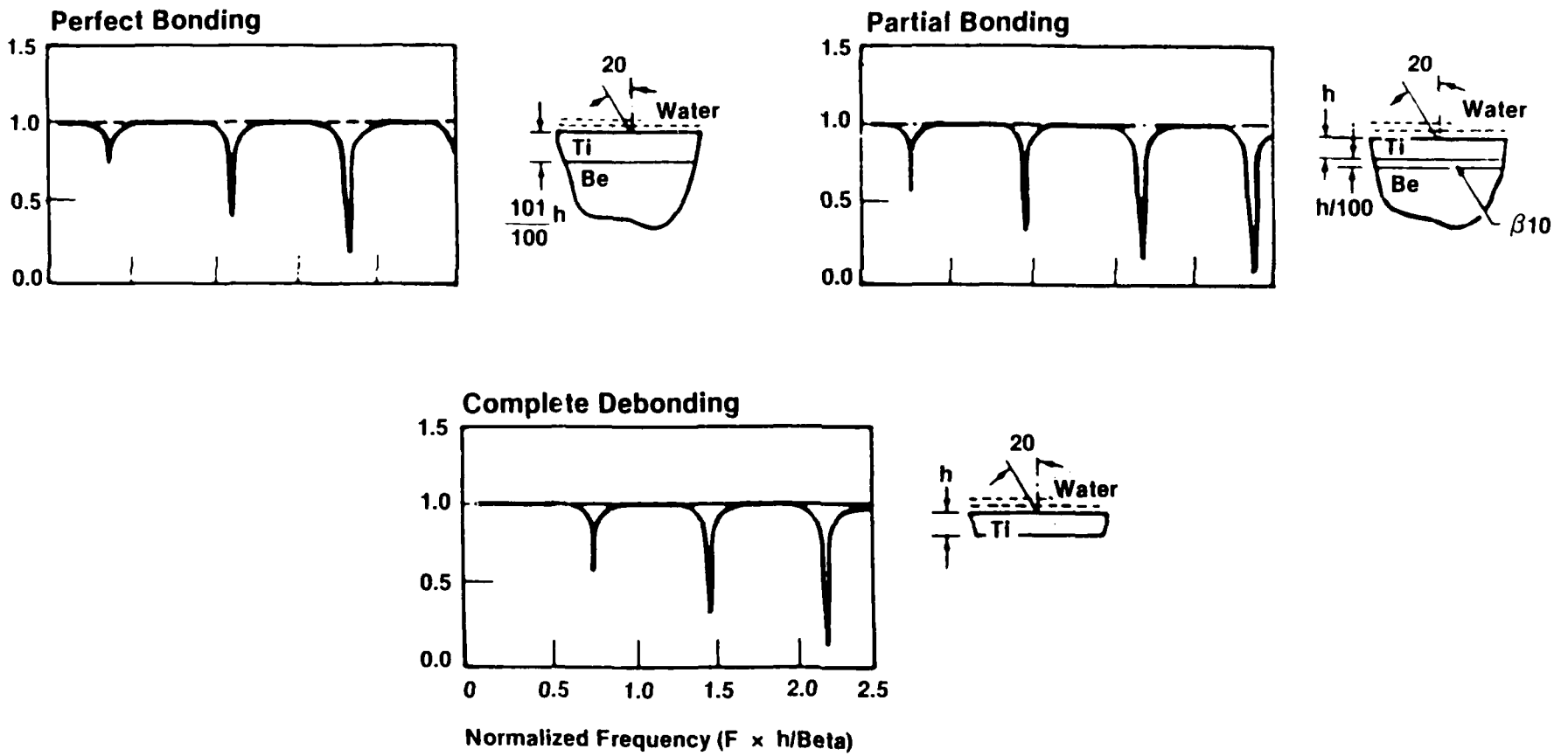
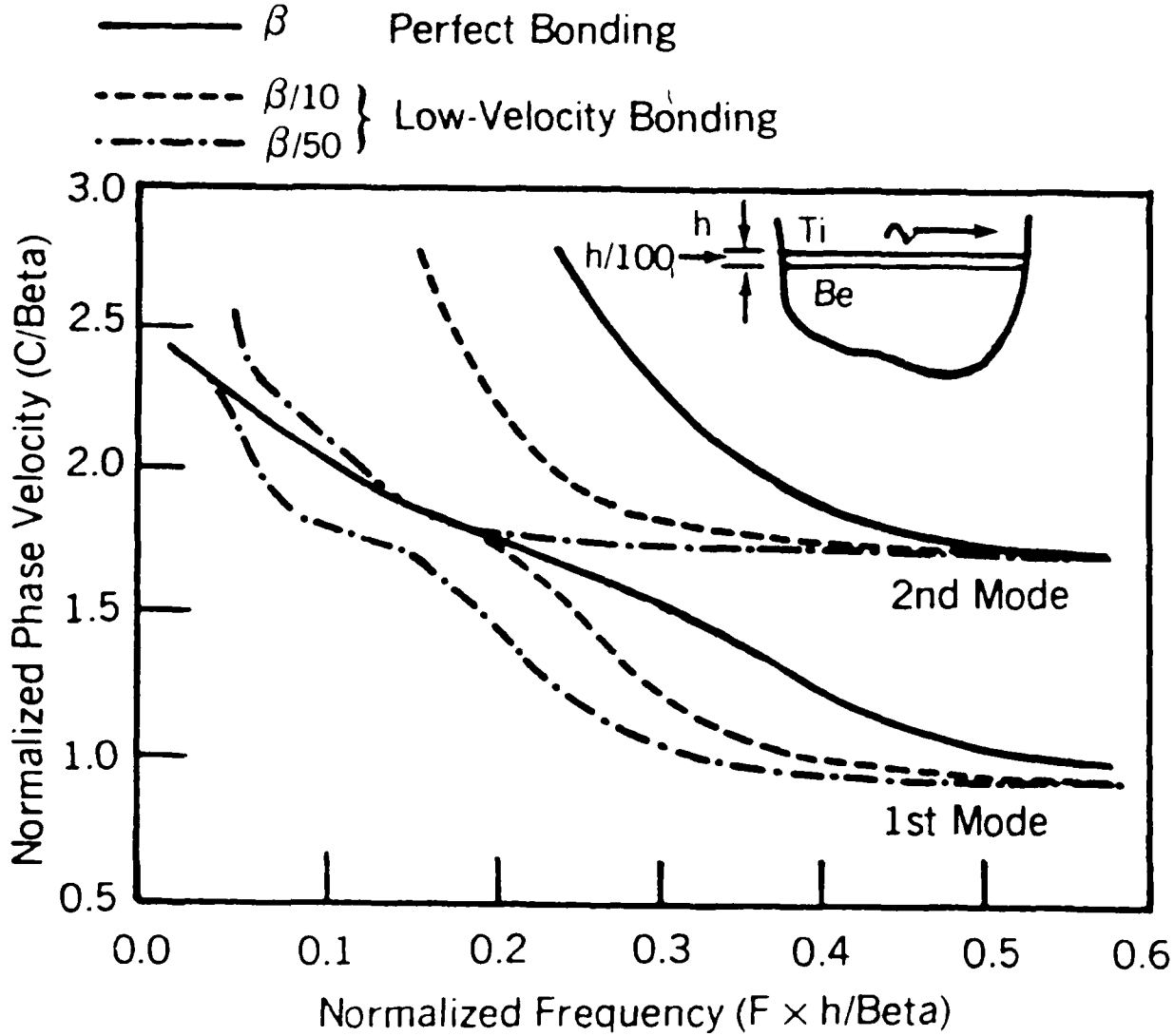


Figure 15

DISPERSION CURVES FOR RAYLEIGH WAVES IN A LAYERED HALF-SPACE WITH AND WITHOUT INTERFACIAL ZONES



NOTE: Note significant change in Rayleigh wave speeds in a specific frequency range.

Figure 16

TECHNOLOGY ASSESSMENT

* CONVENTIONAL METHODS DO NOT PROVIDE PARAMETERS RELATED TO INTERFACE QUALITY.

* LLW PROVIDES A GREAT POTENTIAL

* COMBINING SEVERAL METHODS AND SIMULTANEOUSLY ANALYZING SEVERAL PARAMETERS - MIGHT BE NECESSARY.

Figure 17

characterize the system. Fortunately now we have computers that are very fast, very capable, low cost, all those nice things about computers that can be used to help us try to overcome this problem of using complex data. One other issue or in this case is how even if we have a way to define the interface properties, the problem is how to measure that in relation to the "strengths". How is that related. Peel tests, what it reveals is that the surface preparation was made good or bad. We don't really have any degrees of quantitative measure of that interface characteristic. One way which was discussed earlier is called the sustained environmental loading test. What that is, we take that system that bonded, load it and expose that, the load is fixed, at a fixed level, expose that to humidity and certain temperature conditions and wear it until the interface loosens up and breaks. What we really measure is something indirect. What we measure is the duration of time that this system is going to hold which is exactly what really we care in the field--how long that system is going to hold, how many years will it stay in business. But it really sounds very strange, we are on one hand measuring modes or amplitude changes and on the other hand we measure time, how long the system is lasting. But somehow in between there is some fundamental relation that make this correlation feasible. And with that I'd like to conclude my talk.

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ULTRASONIC SHEAR WAVE AND LAMB WAVE AMPLITUDE MEASUREMENTS IN ADHESIVELY BONDED STEEL PLATES

This is a collaboration between Stanislav Rokhlin, Mr. He and myself on work on ultrasonic shear wave and Lamb wave amplitude measurement of adhesively bonded steel plates. Another co-author is Gil Chapman from Chrysler Corporation. This work is funded through a Challenge Fund supported by Chrysler. So I guess you figure it has something to do with the automobile industry. We presented a couple of basic papers day before yesterday, one by Dr. Peter Nagy and the other by Dr. Stan Rokhlin where we discussed some of the fundamental aspects of different wave propagation which are more desirable to study adhesive bond.

The candidates to interrogate adhesively bonded joints are the ones where there are some shear stresses that can be introduced into the system and these are either various type of leaky Lamb waves, guided waves, or various shear waves, and the type of waves we are going to discuss is horizontally polarized shear waves as well as various types of Lamb waves and as it's known, especially SH waves cannot be generated in an ordinary way so we are using EMATs.

The specific problem which we are addressing, it's more along application. Here we have a real problem.* We have a car door and there are some adhesively bonded joints here. The manufacturing of these car doors obviously needed some technique to evaluate the strength of these bonds, so that's the fundamental problem which we are addressing. Several people already pointed out conventional longitudinal waves are not very sensitive to this type of problem because they easily transmit through thin layer without any information, so you need some other type of mode. As I already mentioned, there are two types of wave modes which we are using, an SH wave with a non-contact transducer, electromagnetic acoustic transducer, and we also use Lamb wave, electromagnetic acoustic transducer, as well as a wedge transducer in some cases to generate Lamb waves. For those of you who may not be that familiar with SH wave I just want to say a few words about it and some of the geometry of the problem.

*No figures are included with this transcript

This is very fundamental and you find it in many textbooks. For the single plate with a thickness of 2H, if you take a coordinance X_1 & X_2, the particle displacement is in the X3 direction and for the three layer problem which we extended the basic problem worked out in Achenbach for example, wave mechanics, we extended this for a three layer problem where we have two plates of the same thickness with a layer of thickness A and elastic property expressed in terms of Lambda constant for the density and adhesive which has twice the 2H thickness has different property. So we're not going through any mathematics.

This is the dispersion curve, it's not in the same fashion that you're accustomed to see as for Lamb waves, because in the case of Lamb waves usually you plot the dimension as wave velocity versus KH, this is a little different plot. You have to rotate this by 45 degrees but basically the lowest mode in a single plate, it's shown over here, if you divide this by omega which you should, then it shows that the lowest mode has no dispersion, it's not frequency dependent.

For the three layer problem, I'll just show you the final expression which one has to calculate. Usually for any of these problems you have to solve the transcendental equation and this is the transcendental euqation which is solved for the different modes and the parameters here are the elastic properties of the plate and layer and the frequency and the geometry of the problem. So this is the equation which you saw and you'll see that you obtain the dispersion curve for the three layer which varied quite significantly from the one layer except for the lowest mode. There is very little change as opposed to the straight line which we saw earlier for the single plate. So the dispersion curve to look into SH wave is not the one we are using but essentially the amplitude of these SH wave which we try to study through some of these bonded regions.

We also used Lamb waves, but I'm not going to go into the details because everybody is familiar with them, but I'll just show you this known dispersion curve which you can find in the textbook indicating the various modes. We are using the S_0 mode also and in a single plate which transforms into the bonded region to A_1 mode. This is the configuration. We use a wedge transducer, it's going back for the transmit to receiver or for both Lamb wave and SH wave we get

some noncontact. Essentially it's contact but for all practical purposes you don't need any coupling. As anybody who worked with EMAT this is not truly noncontact, you can have some small liftoff but the sensitivity significantly decreases.

The particular type of EMATs we are using is designed by George Alers and Company and it's shown here that you've got these magnets and the spacing between the magnets are giving you the wavelength of the different type of waves so we are dealing with very low frequencies. This is just a general layout which indicates that Hardy-Lawrence force is in the plane due to the cross product of the current generated and the external magnetic field and so we can obtain truly an SH wave as it propagates along the plate.

We've prepared our own samples which specifications and the different type of joints which we have is shown over here, the commonly used lap joint. We are using steel plates and the total thickness with the joint together is 0.05 inches. We varied the overlap region to study for example attenuation there. The other type of configuration we use is a long joint where the plates are bonded together through the whole region. We're also using some configuration which essentially is part of the car door. This is the part which we want to study and finally we are using virtual car door for our final evaluation. So we are using two different types of adhesives and, well, before I show you the adhesive I'll show you how we try to introduce some defects.

We take a thin plastic film in various lengths, we are putting on a surface before we apply the adhesive, so this way we can generate different length of misbond in both longitudinal and transverse defects of various widths and lengths. Initially we thought we wanted to simulate the weak boundary layer but essentially what you have is an adhesive with a defect between the adhesive and the adherent so instead of calling weak boundary layer this is just a boundary defect and I think we may even use BLD but it's no confusion between weak boundary layer and boundary layer defect. The curing process shown over here, we use two different types as I mentioned. These are designation of some commercial trade name for these adhesives. In the first case we have a three step process, it's heated up to a certain temperature through a certain time, then it's cooled and it's heated again to lower temperature and finally we have an additional

heating. The second type we just heat it up to 170 degrees and up to 20 minutes and then cool it down to room temperature. So these are two types of curing processes we apply to the steel plates. The other experimental setup is very straightforward. We generate ultrasonic waves at the high power oscillator like a MATEC or Ahrenburg* using continuous wave and the received signal after it passes through the joint is displayed on an oscilloscope and we can do all sorts of analyzing, digital oscilloscope for example and we can study frequency content and whatever.

The first thing I'd like to show is that in using SH wave amplitude measurement we can actually monitor the curing process if we measure the transmitted amplitude of the SH wave as a function of time. Then it starts out at the certain relative amplitude and increases up to a certain point to about 20-25 minutes after when it levels off. This is for an epoxy so we have a much lower temperature but it's clear that at that point solidification takes place, the amplitude of the horizontally polarized shear wave will not change anymore so this has achieved the solid bonding.

In order for us to decide which mode is more sensitive to apply for real application we have to be aware of what the adhesive thicknesses are. In aerospace industry the adhesive thickness is I know there are 0.1 or 0.2 mm, in automobile industry at least for this particular application the adhesive thickness is much higher, maybe up to as much as 0.5 or 0.6 mm. The first study we should try to do, which is kind of expected, is to measure the relative amplitude of the transmitted SH wave as a function of layer thickness and as one would expect, the amplitude will decrease but sensitivity of this device is such that after about 0.15 or 0.2 mm adhesive thickness then you will not have significant signal to interpret. So for some application for thin layers that could be very informative but for thicker adhesive layers we had to go toward Lamb waves. But before I do that I just want to show you that even though the amplitude that we are measuring is not directly the strength of the adhesive, we find a correlation I guess like everybody else. You know that ultrasonically, from elastic waves, you don't really get direct information. Indirectly you also find that by measuring the shear strength as a function of adhesive layer thickness and that's also well known you have quite a bit of spread but here again the strength is inversely proportional to the adhesive layer thickness so

*actual spelling may be different than shown

clearly one would expect some correlation between the measured amplitudes and the shear strength.

I'm going to show you some of these. This is a little different one. Rather than showing you the function of thickness for a constant thickness, if you introduce a boundary layer defect (BLD) in one of these defects which we introduced and if you make measurement of the SH wave amplitude the function of shear strength, you'll find that there is some correlation here. The one- and two-sided measurement means the following. If there is some question that this particle or guided SH mode is developing in one of the layers, in the adhesive, or in the total structure and because of that we are making measurement by placing the transmitter on one side and the receiver either on the same side or on the other side and what we see here, the first curve represents just attenuation essentially because what we're measuring is the relative amplitude of the function of distance so the slope of this curve is the attenuation for a single plate which is almost zero because the steel plate has a very low attenuation as opposed to the bonded structure. These are the two lines almost parallel although there is slight change of the slope but whether you are measuring the received signal in the same side or the other side approximately you have the same kind of attenuation curve indicating the fact that the bonded wave, the SH wave, is in the total structure other than just in one of the plates. A few other results here. With SH wave for example we are studying the variation of SH wave amplitude as a function of width of a defect and clearly the larger your defect the smaller the amplitude that transmits it. So it's just an attenuation mechanism. Turning over to some of the Lamb wave results. For a thicker adhesive layer like 0.5 or 0.6 mm, we've been using certain type of Lamb mode, as I mentioned S_0 mode and here there's quite a bit of spread but attendance if relating the Lamb wave amplitude to adhesive shear strength shows that there is some correlation and I guess that's the one which more careful modeling is needed but as a practical tool in industry perhaps it can be used to evaluate shear strength provided you improve a little bit the accuracy of this.

I just wanted to show you a couple more of the Lamb wave mode. Basically you find the same kind of behavior as for SH wave that you have, if you introduce a defect of the boundary then the transmitted Lamb waves are going to also decrease with the defect size so you get some indication about boundary layer

defects. When we go to the actual automobile door then we try to apply the same technique. This is the automobile door and this is the adhesive region that we want to mention so here we place the transmitter and couple the wave and the wave of course has several possibilities of going through the adhesive region as well as going around the plate to the receiver and we've been just beginning to investigate this. It appears that we are going to be looked three different cases but first of all whether we have adhesive there or not can we tell the difference number one number two. If the adhesive is cured sufficiently or not sufficiently can we tell something different about the received signal. What we find is that rather than measuring the absolute amplitude, invariably we're going to get at least two signals close to each other, one which will be the S_0 mode as it propagates around the plate and the other one which changes from S_0 to A_1 in the bonded region and that comes through the plate to the receiver. So these are the two signals with relative magnitude we are looking at and if the adhesive is strong, the A_1 modes have a high amplitude relative to the one which are going around the plate, then we believe that we have an accepting criteria and so this is the kind of result I like to show. As I said we are generating a Lamb mode, S_0 mode. We have a very large signal here. This is a good bond, an incompletely cured bond and unbonded case. This is a digital oscilloscope, we display the amplitude as well as the frequency but I like to concentrate only on amplitude. The first mode which has the signal that arrives is the one which, transmitted through the bonded region, is much larger than the second one. Here in case of the good bond and an incompletely cured bond, two signals are almost the same order of magnitude and they cause this interfering behavior. For the unbond, neither of the two signals are high enough because there is no adhesive there at all. So we believe that this is the kind of accept/reject criteria first that we can apply for a real situation.

There is some theoretical analysis which I really don't have much time to go into it, but I just want to show you here. This is a calculation where it shows that you have S_0 mode for a single plate and how the mode for the double plate with the adhesive is going to behave and at this point where we are for the particular frequency and layer thickness from the single plate to the adhesive these are the two, this is the jump which takes place. So these are the two signals essentially which we are comparing to each other and the relative amplitude, they're quite different and we believe that we have a good bond.

So in conclusion I'd like to point out that use of these plate modes such as SH or Lamb modes has significant advantages over bulk modes for complicated shapes and can be applied such as to the car door. I think it's very clear that it works for complicated shaped joints and amplitude methods which we are applying here gives a gross effect, a gross evaluation. Obviously for finer details you may have to look into the velocity measurement or setting more of dispersion effects but because of simplicity, relative amplitude measurement, amplitude measurements are not easy, but relative amplitude measurement could be useful just to have an accept/reject test. SH waves are good for thin layers but for thick layers you want to use more Lamb waves of different types.

Krishnan Balasubramaniam
Drexel University
Philadelphia, Pennsylvania

ULTRASONIC OBLIQUE INCIDENCE TECHNIQUES FOR ADHESIVE BOND INTERFACE QUALITY EVALUATION

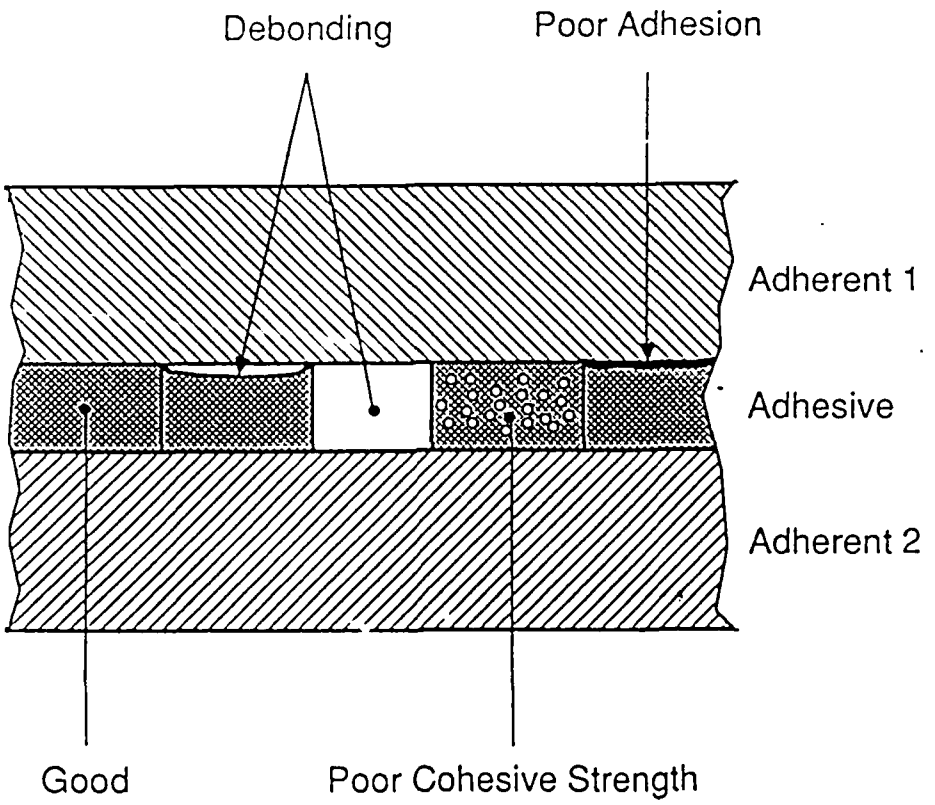
The title of my talk is Ultrasonic Oblique Incidence Techniques for Adhesive Interface Quality Evaluation. My name is Krishnan Balasubramaniam and I'm from Drexel University, Mechanical Engineering and Mechanics Department. Before I start, let me say a couple of words about Drexel University and what we are doing there. We have about seven faculty members involved in ultrasonics with particular interests in NDE. Five are affiliated with the Mechanical Engineering Department, one in Electrical and one in Civil Engineering and we have about 20 graduate students and about 20 undergraduate students working on ultrasonic and NDE problems. We are concentrating mostly on composites, adhesive bonds, welding problems and certain biomedical and civil structure problems also. I'm a graduate student going for my Ph.D there.

In a Workshop such as this several things get repeated more than once so please forgive me for repeating maybe what previous speakers have already mentioned. But looking at what we are trying to evaluate here, bond structure between two metals, can be magnified as seen from Slide 1, we have two adherends and an adhesive in between. There are many types of defects that can occur but simplifying this problem we shall classify them into three categories. One is the disbond and the second was the weak cohesive strength, and the third one is the interface problem. As probably we have come across in the previous talks, disbonds are not very difficult to detect. Of course, for weakness there are techniques like C-scan, Fokker bond testing, impedance resonance techniques, which can all be used for cohesive weakness and there is a lot of progress going on right now. But interfacial weakness which essentially means that there is a contact between the adhesive and the adherend but there is no real adhesion, in other words, it's unable to withstand any shear loading which is the problem which has been faced by many industries and of concern to us are the aircraft structures. Right now there is no standard solution available and we are here trying to evaluate the potential of some.

Slide 1

PROBLEM STATEMENT

A TYPICAL BOND INSPECTION PROBLEM CAN BE SIMPLIFIED AS BELOW :



Classified into three main types :

* Disbonds - Traditional C-Scans

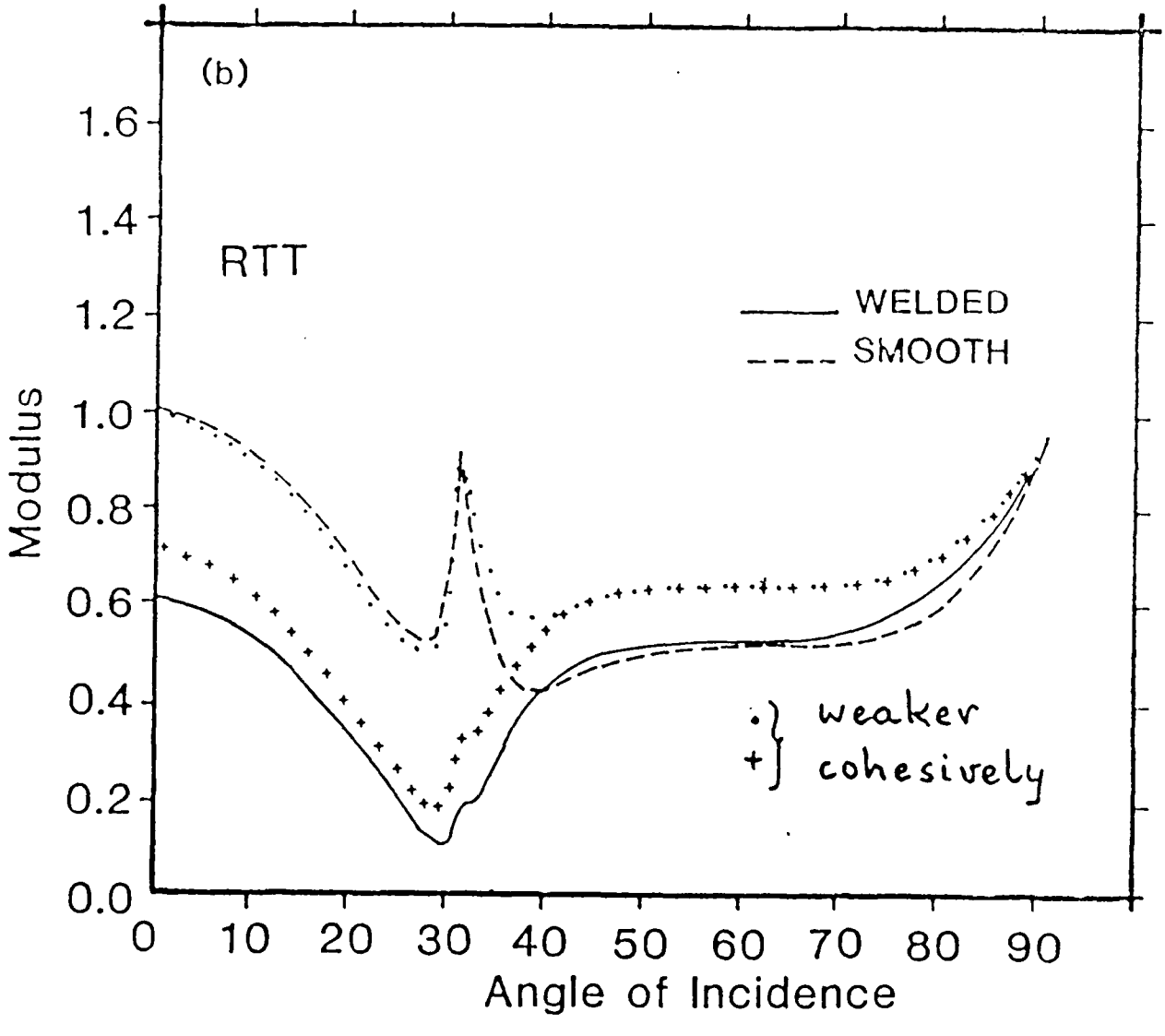
* Cohesive weakness - C-Scans, Fokker Bond tester, Impedance and resonance techniques etc.

* **Interfacial weakness** - Most difficult problem
  - **No standard industrial solution available.**

As a solution to several current problems in the NDT field, better processing, better transducers, array probes and finally even expert systems are getting introduced into our systems. All these help us in NDE, it makes life easier, it makes things quicker and so forth, but unfortunately there are still problems such as the interfacial problem which needs to be tackled and the best way to tackle it is to go back to the wave mechanics approach and look for solutions there and then come back to the improved features which should help us to practically implement these techniques into the industrial field. When I say wave mechanics, this may or may not be isotropic material or composites, in an ideal situation you like to have maximum information from any given material but we are bound by time and by practical limitations that we may not be able to get all the information we need, and presently we're using mostly a normal incidence longitudinal wave technique, traditional C-scan and we are using only amplitude and time information. But more recently, because the computer facilities have improved and so have the mechanical instrumentation facilities, we are able to proceed and look into oblique incidence techniques with more confidence. In oblique incidence, when we either send a longitudinal or a shear wave at an oblique incidence it is possible to generate, due to mode conversions, a longitudinal or a shear wave inside the material and also we can generate Rayleigh waves, plate waves, interface waves, and so forth. The advantages of these different types of oblique incidence can be well appreciated in this fashion. The physics of these waves are different from a normal longitudinal wave. In a normal longitudinal wave all you have is a compressional wave going with vibration components mostly in only a specific direction i.e., normal to the plane of incidence. But we can by oblique incidence generate displacement components in various directions. We can also generate multiple modes, again leading to displacements of different types within a structure and these different displacement components can be used effectively to look into subtle defects within any material. Now for instance today I'm going to talk about three oblique incidence techniques. The first one involves oblique incidence shear, the second involves plate waves or lamb waves as some people call it, and the third is the critical angle technique. Now plate waves and critical angle techniques have an inter-relationship because they are sort of related which I'll come to later. Now shear waves have distinct advantages in looking into bond interface problems. The primary reason is the tangential to the interface or tangential to the bond line displacement components inherent in shear waves. The best possible shear wave angle would be at normal direction but normal shear

waves are difficult to generate and more difficult to use for any practical scanning purpose. So instead we will use an oblique incidence shear wave, in other words, we send in longitudinal wave into the structure and by mode conversion look only into the shear components. The shear waves at an angle have components both in the normal and the tangential directions and this tangential component is what we are interested in and hope for sensitivity to interfacial weakness because in an interfacially weak bond, the normal strength is pretty high but when it comes to shear, it fails. So we're looking into the shear weakness problem. Second is plate waves. A plate wave mode has different displacement components across the thickness of the plate which it is travelling. So we can look into specific modes which has the best sensitivity to interfacial problems, and finally critical angles is more or less a quasi-local influence of the same plate waves. When we go to a real experimental environment we feel there is a need for some theoretical background (to set guidelines) and to make it a science. We need some kind of a modelling technique which will give us the specific parameters which we can use effectively and save a lot of time and effort. Now let me first introduce to you a model which has been around for almost 20 years but we've applied it for this problem i.e., using the spring model K_n and K_t. We model the primer or the interfacial properties by a spring constant K_n and K_t and we see that the stress components are related to the displacement components by the K_n and K_t. So in other words, the stresses are continuous but the displacements are not. Now by weighting the K_n and K_t we can simulate interfacial conditions, either a disbond or a weak interface or a good bond. This can be done by changing the values of K_n and K_t as shown below. K_n and K_t when it's very, very large is equivalent to having a very rigid interface, so if K_n and K_t tends towards infinity we have what is a well ordered situation, an ideal bond. Now if K_n and K_t goes to zero what we have is a total disbond but the most important situation which we are interested in is when we let K_n tend to infinity, K_n is very high so the normal displacement gets transferred very fast but K_t which is the tangential component displacement do not transfer which simply is what we call an ideally smooth condition. Now in a real situation of a weak interface we have a condition somewhere in between and where we are we don't know yet. Now K_n and K_t values can be a function of the material components of a primer and we have used many primer constants to evaluate and estimate these parameters. A result from using this model as shown in Slide 2 looking at is reflection coefficients from a shear wave impinging on the interface. We have graphed the reflection coefficient modulus with angle of incidence. When we

The modul of the reflection coefficient vs the angle of incidence in the case of aluminium/epoxy with welded and smooth boundary conditions for incidence of the transverse waves and for two different material properties of the epoxy resin.



change the angle of incidence the reflection coefficient changes and we have four different cases analyzed. First concentrating on the dark and the dotted lines and we see that this dark line is for a welded condition, that's a good bond. The spotted line is for a smooth condition. As I mentioned before when it's on a 90 degree or on a normal incidence there is sufficient sensitivity for the shear waves but it is difficult to generate and more difficult to scan the specimens with it. So instead we try to use what is the best angle possible, that is around 30 degrees which happens to be the first critical angle of the material. Now we feel there is sufficient sensitivity between a good bond and a bad bond. The points you see here represent instead of changing the interfacial properties we change the material properties of the adhesive simulating a weakly cohesive bond. We see that whenever there's a weakness it also tends to go towards the smooth conditions. In other words we are always in the safe condition, we don't have cohesive and adhesive properties crossing each other and going in different directions which will create a problem. We feel quite safe in using the model and proceeding with experiments. Going further with this model we tried to evaluate the influence of frequency and we found out that as you increase in frequency, there is a tendency to detect subtler defects. To look at very small, very subtle defects it's possible but we have to go to very high frequencies. Again the influence of an angle, we can see here, the reflection curve here for 30 degrees is simply much larger than a 60 degree or any other angle. So we chose a 30 degree and our own 15 MHz for our experiments.

Now, I will summarize what we think shear waves can be useful for. Oblique incidence shear waves because it produces both tangential and normal displacement components have a sensitivity to interfacial weakness problem. Because of this there are several other inherent advantages of using shear waves. One of the major advantages is because of a slow velocity as well as the oblique incidence, it is possible to achieve better axial resolution. Thus, you are able to isolate echoes much better when you are talking of thin multilayer bonding situations. So we can probably either go to a lower frequency or it's still possible to isolate echoes easily.

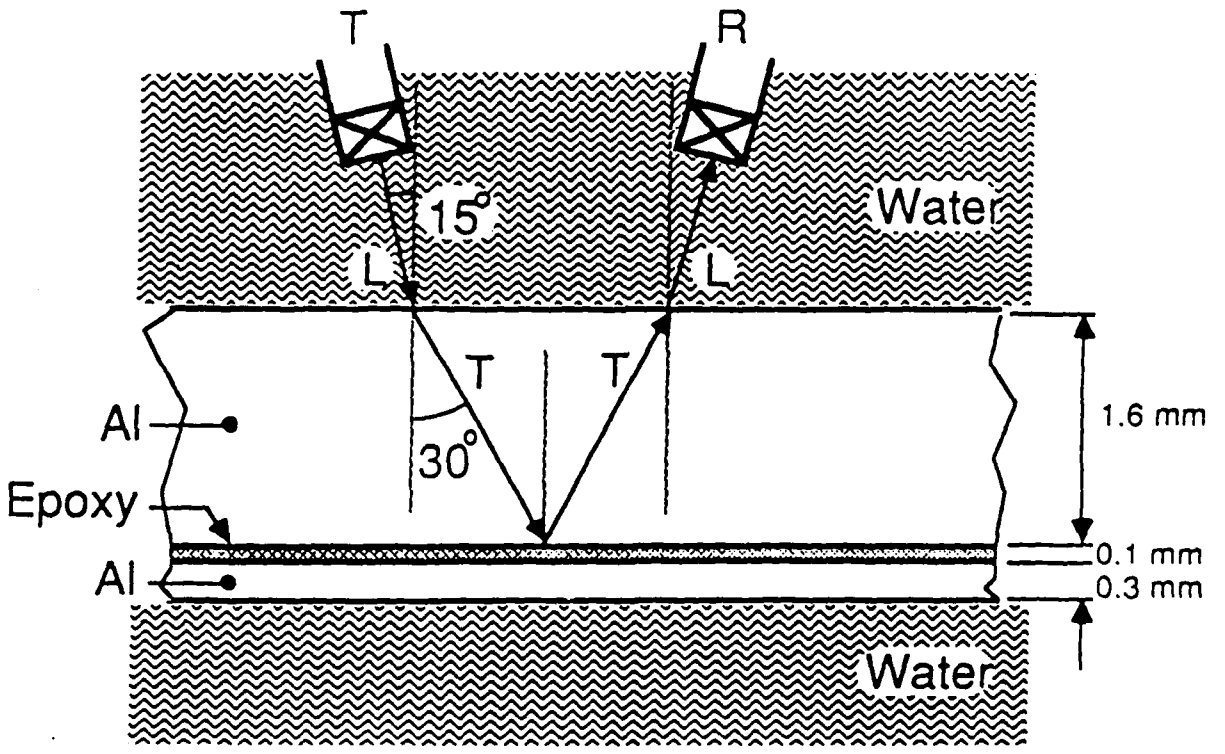
Before we start any experiments, we have to prepare specimens and these specimens were prepared by bonding an aluminum onto another aluminum substrate by epoxy adhesive. We simulate a weak interface by going through all of the

preparation of the surface of the upper and the lower aluminum and finally just before bonding a microscopic layer of Teflon is sprayed on top of one of the surfaces and because we don't want the presence of Teflon, we wipe off the Teflon thus simulating a weak interface bond. Test results by destruction prove beyond any doubt that it's an effective way of simulating a weak interface. There is very little influence of the Teflon contamination. The experimental technique as shown in Slide 3, has longitudinal waves coming at 15 degrees mode converts 30 degrees shear wave and the shear wave which goes back 30 degrees and back to 15 degrees in water on an immersion mode but we can also use a contact mode for such experiments. A typical result is shown in Slide 4. This is a scan along the center of the specimen and we see that this line here represents the sensitivity we got from a longitudinal wave. So there is a little sensitivity from the longitudinal wave-normal incidence. But when we use shear waves we obtained excellent sensitivity, we're talking in terms of 4-5 dB differences with shear wave. After having seen a typical result like this we proceed to some feature maps of such bonds (see Slide 5) and we simulated one portion as a good region and another as a Teflon contaminated region. But as you can see here towards the ends there has been a little corrosion. You can see that using shear waves we are able to tell the difference.

That kind of summarizes our efforts in shear wave techniques. Now we proceed on and go to critical angle and plate wave techniques. The critical angle technique as I show you here is to look for reflection factor signature with angle of incidence. So as you can see if it's a plate and if your wavelength is quite compatible with that of the plate what happens is you get dips in reflection factor. These dips are minima in the reflection factors, represent what we call critical angle and these also represent a generation of "A" mode in a thin plate. If these critical angles can be established for any specific frequency times thickness product, we can come back to what is called the dispersive curves which represent phase velocity relationship with frequency times thickness. From the angle to phase velocity conversion is by using the regular Snell's Law approach. We can by looking at the minimas in reflection factors come up with dispersive curves and this is the theoretical approach which we have employed to get our dispersive relationships. Before going on to the actual dispersive curves I would like to tell you some of the advantages of using such critical angle and such plate wave techniques.

Slide 3

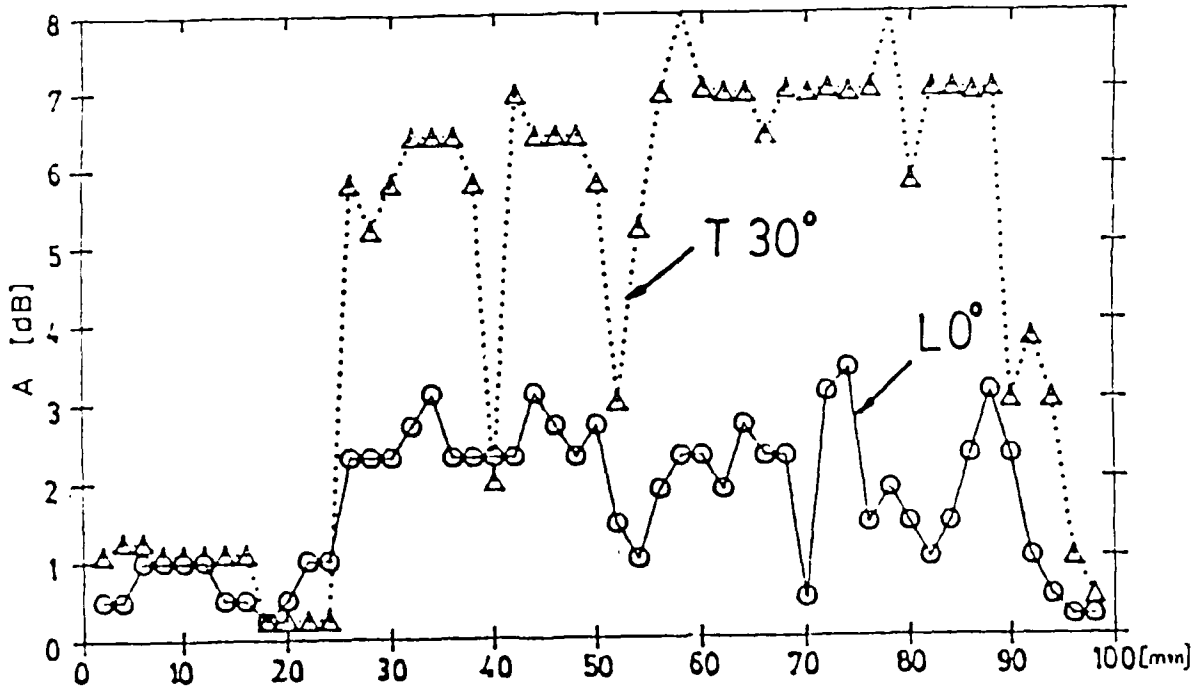
THE OBLIQUE INCIDENCE SHEAR WAVE F-MAP EXPERIMENTAL CONFIGURATION



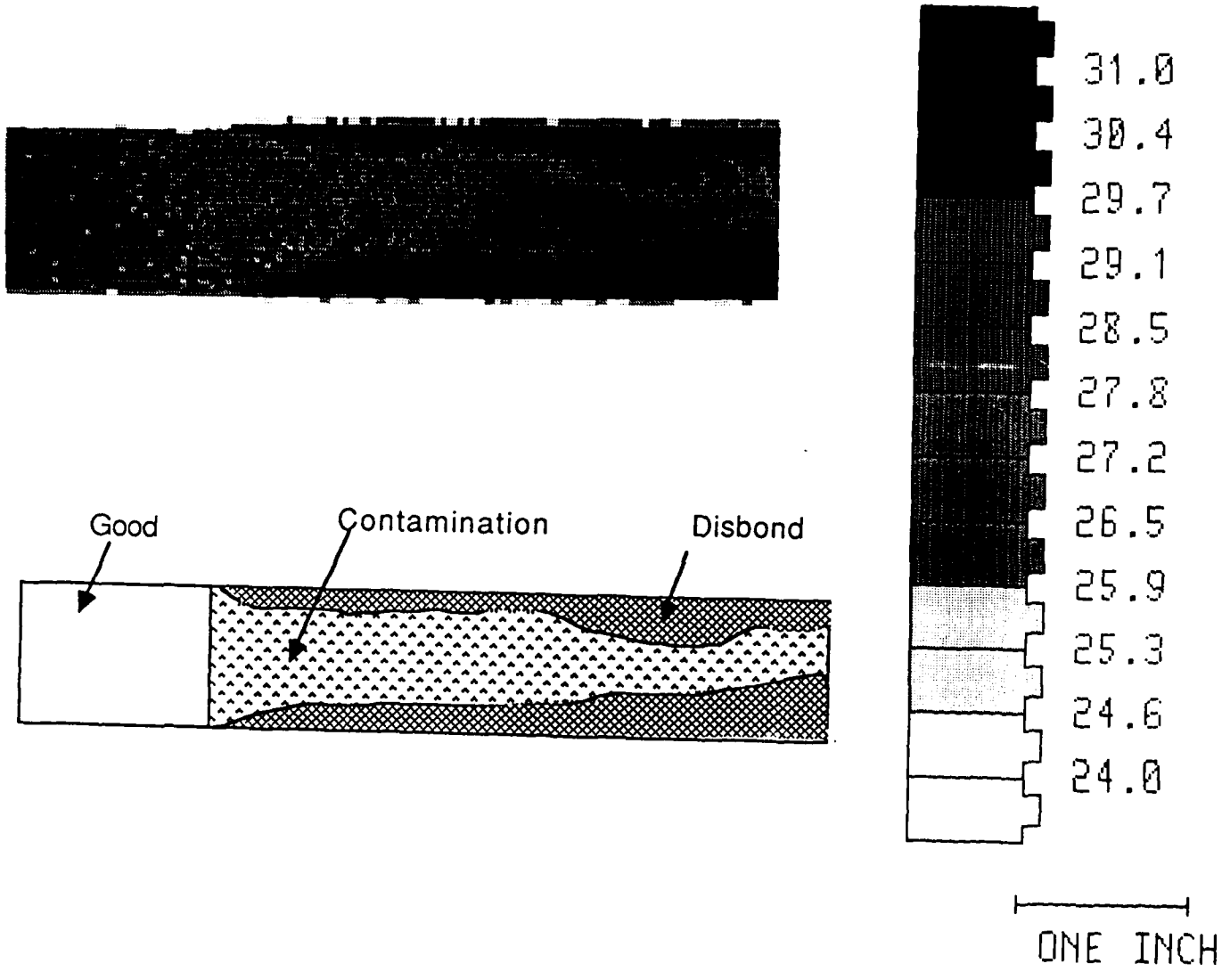
Slide 4

A TYPICAL SHEAR WAVE SENSITIVITY RESULT

ALUMINUM - EPOXY - ALUMINUM



Slide 5



10. Feature maps using Gaussian filters of the (a) 10 MHz and the (b) 20 MHz. response from the broadbanded transducer showing better sensitivity to the weak interface regions when compared with the result from the broadband signal.

Critical angle techniques can be used either as a reflection factor curve signature. In other words a reflection factor curve is quite dependent on the material properties so if you have reflection curve factor signature, it's possible to estimate what the material property is. But it is very complex. The more easy way of doing it is to look for just the minima or the critical angles. Instead of using the signature along angle if you use the signature along the frequency you can also get what we call resonant frequencies which also are some kind of indication of what the material is. These minima are representative of plate wave generation and an accurate measurement of minima can provide the material evaluation as has been done many times before by many people. A typical result of such evaluation on our adhesive interface weak bond approach is shown here. Instead of using the reflection, we use a through transmission technique which almost gets the same sensitivity and we send ultrasonic wave, it goes through the plate and hits a reflector, comes back and it's received again by the same transducer. We look at the signature with angle, in other words we change the angle of this specimen, inclination of the specimen, we get signatures such as amplitude vs. incidence angle. I'm only going to show you a typical example (see Slide 6). A contaminated region when compared with a good region shows sufficient sensitivity and as you can see here there's two different critical angles or two different modes being generated. The first one is at around 15 or 16 degrees, the second one is around 35 degrees and you can see that even though there is this little amplitude change around the 1st critical angle, the more significant is the second mode, which has a big change in amplitude plus also as you can see there is a shift in the angle. Now a shift in the angle represents a change in the wave velocity also. So you can either look for wave velocity difference or probably amplitude difference, when you're talking about critical angle or plate waves. What are the advantages of using plate waves? First is it's got different sensitivity to different anomalies and hence you can characterize the anomalies. There is very little dead zone along this plate so really you're seeing almost every single part of the plate. Careful selection of the mode can give specific information about the specimen. Each mode is unique, and essentially possesses different degrees of sensitivity to anomalies and finally inhomogeneous leaky waves are easy to receive. Also the time of inspection is drastically reduced because we're looking at a line of scan instead of a point by point scan. So we have many advantages of using plate waves. Let me acknowledge that while using plate waves one of the major problems which we face is change in thickness of the bond because it's very difficult even in an

Slide 6

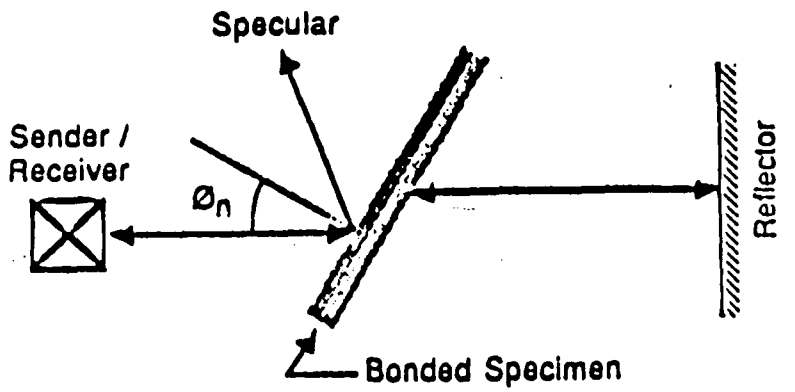


Fig 3a. The double through transmission technique using high precision angle variations.

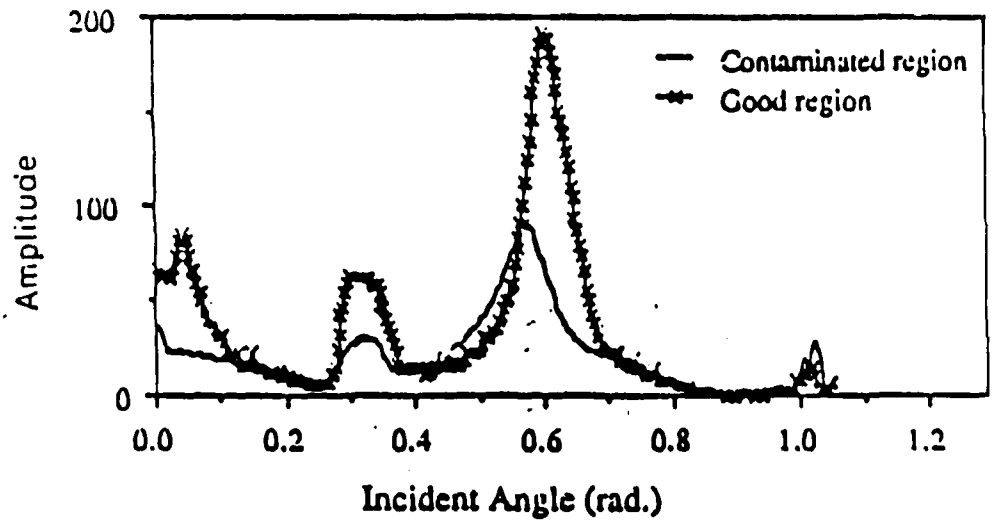


Fig 3b. The amplitude of the double through transmitted signal .vs. angle of incidence for a Al - Ep - Al problem with two different interfacial conditions. The maxima's represent the critical angles.

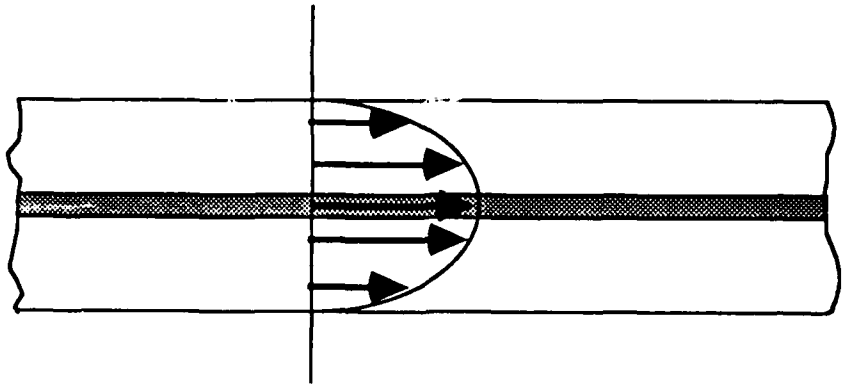
autoclave procedure to maintain the thickness of the bond very accurately and we're talking in terms of 0.1 mm change can make a big difference in the wave velocity or wave amplitude measurements. We have to somehow compensate for the thickness and I would like to show you how we are trying to compensate for the thickness. As I said, each mode has an individual response to the material property, in other words, it has its own individual response to thickness, and has its own individual response to interface. Somehow we have to look into more than a single mode and isolate our anomaly which is the interface weakness. Even though these figures are not exact, because we haven't finished our displacement studies yet, fictitiously looking into what a plate wave mode displacement is, as shown in Slide 7, this is probably one of the very fundamental modes. Mode "A" had very little displacement on the surface so probably it's quite insensitive to any surface deformation but very sensitive to either a change in thickness or the whole material property. Again, Mode "B", this is not very sensitive to changes in surface because there is very little displacement on the surface but it's probably more sensitive to changes in thickness of the bond. Look for instance at Mode "C" and you see that the maximum displacement is along the interface here and such modes are what we're looking for, because this will have the maximum sensitivity to any interfacial problem.

We proceeded as shown by our model before and we calculated our dispersive relationships for two different cases--a welded condition on both interface and smooth welded conditions. Slide 8 is for a three layer problem of aluminum-epoxy-aluminum. As you can see, here is frequency times total thickness versus velocity and these dotted lines represent the smooth or the weak interface problem and the black lines represent a good bond. There are some regions where plate waves are not sensitive to either any interface change or not even to any thickness changes. For instance if you're looking at mode M2, this is extremely sensitive to any thickness change but it has also got very little difference with change to any interfacial conditions compared with mode M3 which has both the influence of thickness as well as big sensitivity to the interfacial conditions. We are looking at one mode which is extremely sensitive to the interfacial conditions as well as thickness and another mode which is not very sensitive to interfacial weakness but is also quite sensitive to thickness. We are going to try and use these two modes and eliminate the thickness influence as much as possible and the way we did the experiment was to send obliquely incidence beam, we had a foam barrier to try to eliminate any direct reflections specular

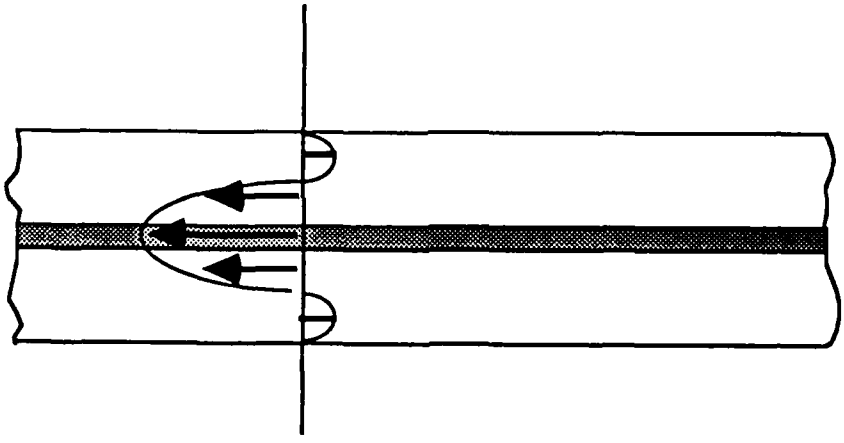
Slide 7

PLATE WAVE MODE DISPLACEMENTS

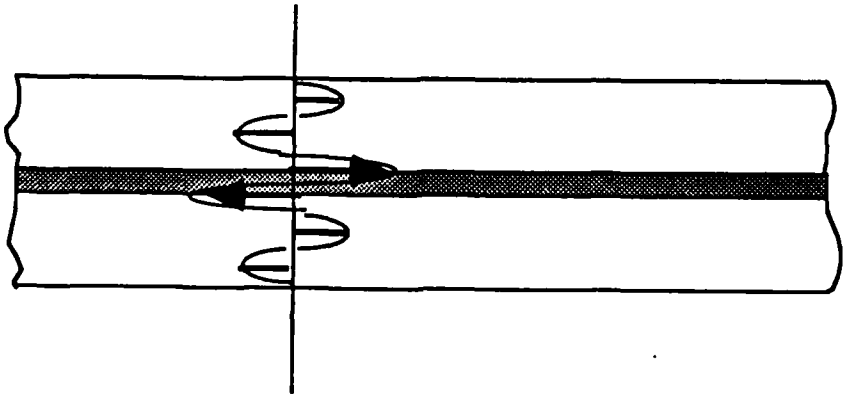
MODE A



MODE B



MODE C



THEORETICAL DISPERSION CURVES FOR A THREE LAYER PROBLEM

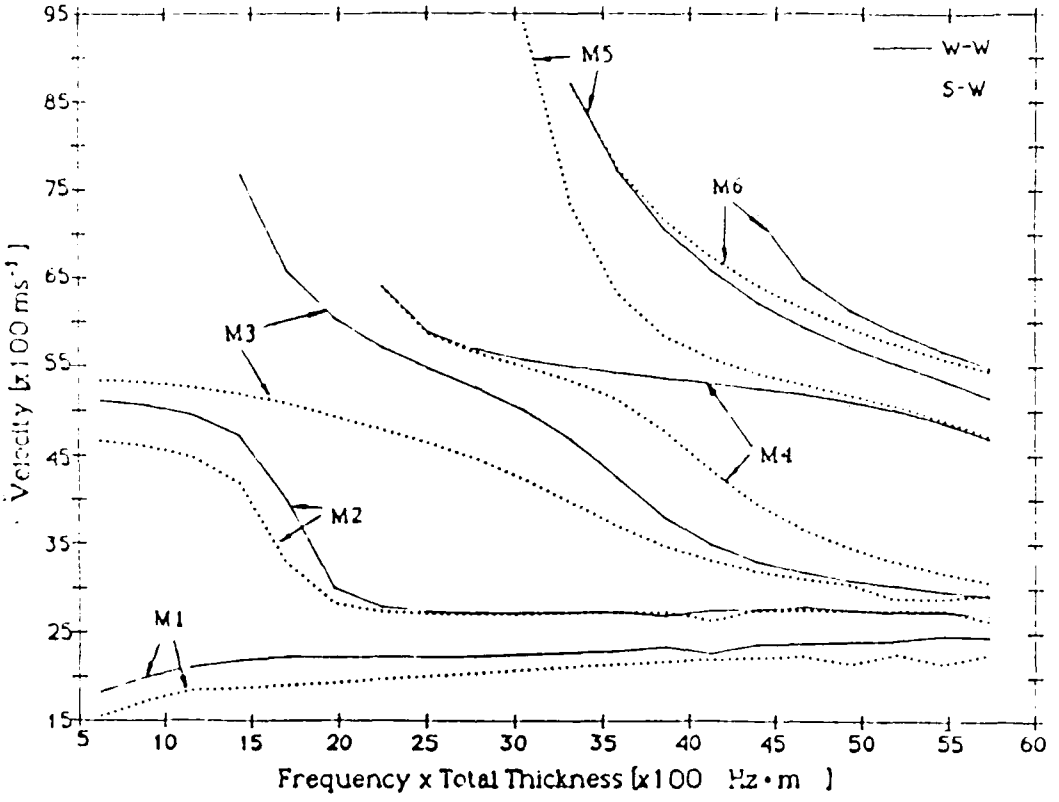


PLATE WAVE EXPERIMENTAL METHODOLOGY

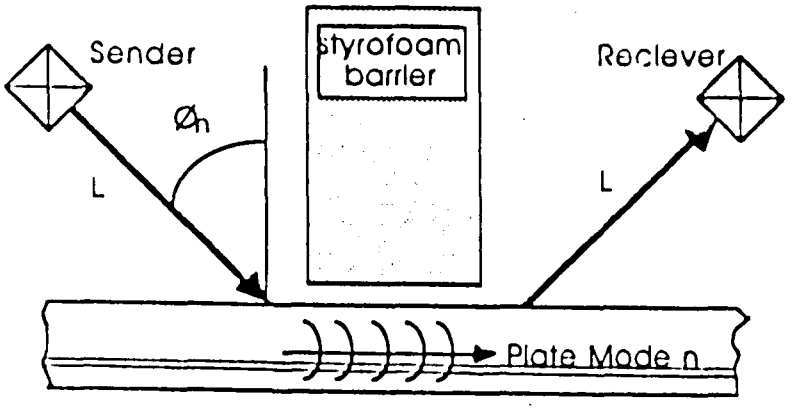
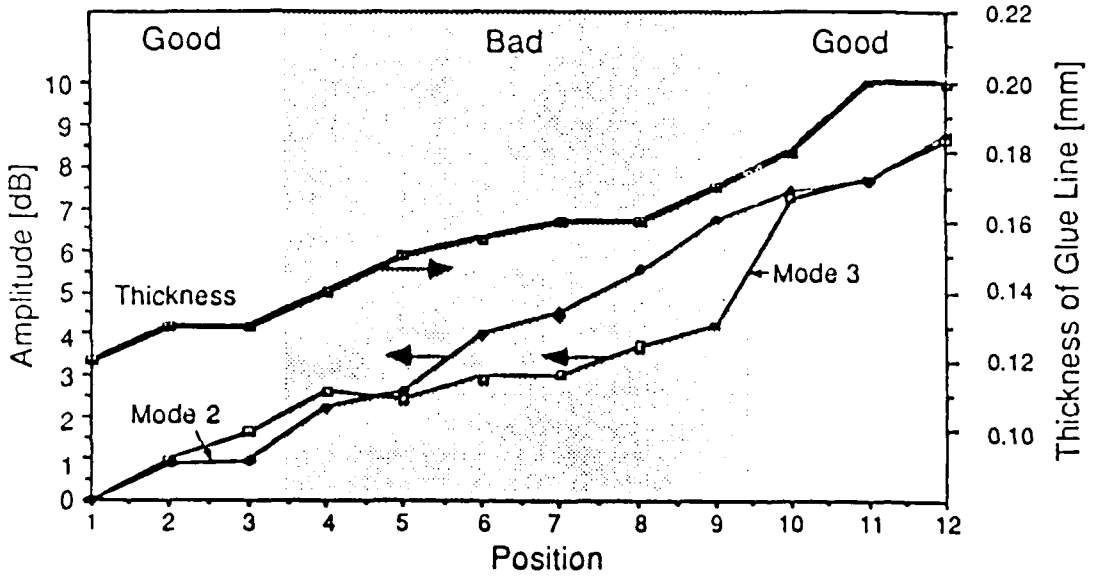


Fig. 8. Global plate inspection in immersion.

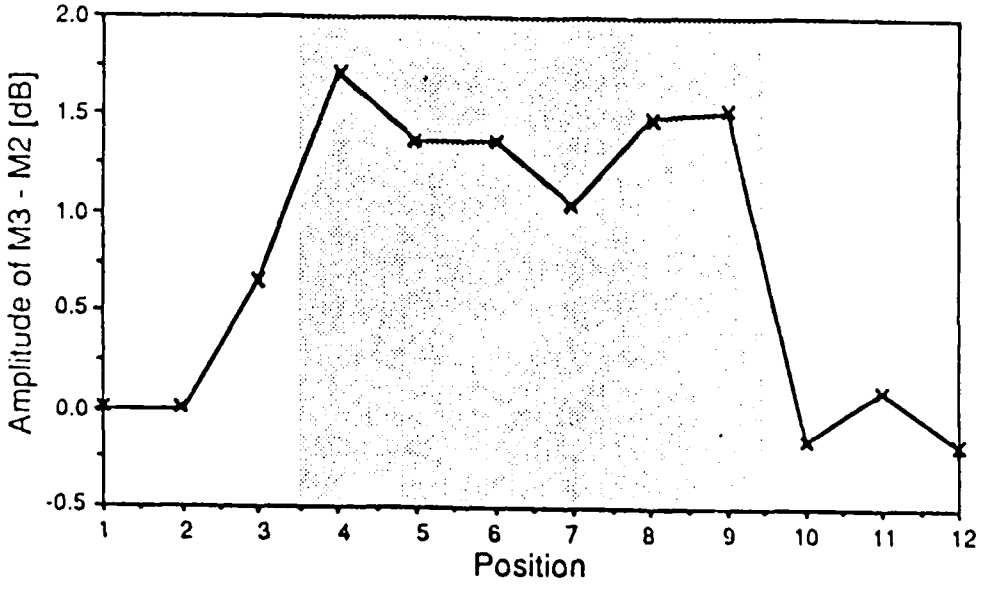
reflections coming off the surface and finally we see the leaky plate waves at the end. Now we can look for both amplitude as well as velocity information, here we are looking only at amplitude information and this first graph shows you three informations (Slide 9). The first information as you can see here represents micrometer reading of a thickness of the plate as we proceeded along the thickness of the plate. You can see it change from 0.12 mm to 0.2 mm. Now even a small change is sufficient to cause alarms and misreadings and misinterpretation of the plate wave results. So what we do is to look into two modes (M2 & M3) as discussed before. These two modes are mode 3 and mode 2. Mode 2 is more sensitive to thickness and mode 3 is sensitive to thickness as well as interface bond. This shaded region here represents a bad region and the good region is on either side. When we are able to use a mode 3 mode 2 as well as the dispersive slope relationships we were able to use a very simple algorithm, filter out any influence of thickness. This does not in any way indicate any weakness but when you come up with such an algorithm we are able to eliminate the thickness influence. This brings us to certain limitations, when can we use these techniques. When we are talking about multiple layers shear waves again become thickness dependent because if you have the influence of the other interfaces but if you use a sufficiently higher frequency like 15 or 20 MHz and if you use a very short pulse or a very broadbanded signal you will be able to make sure that this wave does not see the other interface and it will be as though it is a single interface problem. So we have to use a sufficiently high frequency when using shear waves. In plate waves you can of course use lower frequencies but you're going to have to have some kind of a thickness compensation technique.

In my final conclusion, I would like to mention here that shear waves sound as a very excellent quasi-local technique for interfacial weakness detection but needs sufficiently high frequencies. Plate waves are promising global methodology and shows good sensitivity to interfacial weakness and speeds up inspection process. During the implementation of plate waves care must be given to thickness changes. An interesting multi-mode approach was illustrated. Critical angle is another material property with sensitivity in a quasi-local mode. Solution to the bond interface problem may be within reach in the recent future. Thank you very much.

PLATE WAVE RESULTS



REDUCING THICKNESS INFLUENCE



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Washington, DC

NDE OF MULTILAYERED ADHESIVE BONDS UNDER COMPRESSION: REAL BOND OR "KISSING BOND" DILEMMA

Well we have heard very interesting talks in this Workshop and most of the talks that we have dealt with had to do just with the bond. There was one talk by Laszlo there on the practical application of these adhesive bonds. This is a real practical application of it and I will describe how we have tried to resolve whether there's a real bond or a kissing bond.

Just to give you some idea of what I'll be discussing in this talk, I'll be discussing adhesively bonded structures, some common flaws which are present in them and beyond that what's the size behind this, experimental technique, and application to naval structure components such as rubber bonded pistons, and then conclusions.*

The theme of the talk is around this problem had come up for us and we were in a firefighting mode to resolve this problem and consequently the work followed the problem. You must be all aware of where the adhesively bonded structures are used. Some of the examples for a military purpose are a radar dome, rubber bonded piston inserts which I'll be discussing here, wing span, and space shuttle, which most of you are aware, apart from the commercial use of it in automotive industry and other places.

The reason we want to discuss the adhesive bonding NDE of it is we want a good bond and if the surfaces are very clean and rough then we can get a good bond. However, that's not always the case, sometimes we have trapped air, sometimes we have film, which is not deliberately put there like Teflon as it was described earlier. Sometimes we have moisture, all these cause the problems because the adhesive or the primer does not stick to the surface and either we have no bond or we have weak bonds in such areas. The purpose of NDE is to detect these bonds before the product goes into service. From the Navy's point of view at present the problem which we have is rubber bonded inserts. These are to make the submarines quiet and the structure which we have here is a three-layered structure, we have steel, rubber, and polyethylene.

*No figures are included with this transcript

So far we have discussed only one interface, two laminars which are adhesively bonded. We have not addressed the problem and there are multiple layers there. Just to give you some idea, the part which we are discussing looks like this. The inside portion can come out and this is the insert here, it has three layers, steel, rubber, and polyethylene. We are interested in the condition of the bond of rubber to steel and polyethylene. As you can see, that rubber is bonded from both the sides and we are interested in knowing the bond condition on both the sides of the rubber as in contrast to which we had discussed earlier, only one surface. There's another picture of this here. One thing I'd like to point out that we have discussed the merit of some other techniques, ultrasonic techniques such as shear waves, leaky Lamb waves, and all this. We have also downplayed the usage of longitudinal waves simply because of the problem of intimate contact or kissing bond, they may be there and there may not be a real bond.

In this talk I will be using the longitudinal waves. The reason for that is first of all I can detect the bond on both the sides through transmission. This means if there is disbond on either side it will show up in the transmitted signal. The genetic problem of adhesively bonded multilayered structures is that they're in mechanical contact but there's no addition and the other problem is that the delamination gap is reduced under compression. If you notice that the rubber is in compression from the steel from inside and the gap can reduce but the lack of adhesion, if there's no adhesion there, even though it's in mechanical contact, we cannot have the shear strength, we are aware of this thing. We found that even though we tried the other thing the other geometry is like leaky Lamb waves, they are not very convenient for resolving this disbond problem. Normally, people have done pulse echo technique for looking at disbonds and they look at the deflector signal. Now the impedance mismatch is tremendously great between the steel and rubber, so consequently the amount of energy which is reflected back is very, very small and if you're trying to distinguish between whether there's a bond or no bond, the signal may be in the noise level as you can see from here. This work was done earlier by George Alers and you will notice that the reflection which is from the front surface and the back surface of the adhesive because the thickness of the adhesive is very small, the time resoution of that is very, very small here. Also the amplitude of the signal is very small. Consequently it is very hard to distinguish this from the noise level, even though one can do the spectrum of this and look at that.

So we decided to use a through transmission technique and in this component we had the access from both the sides and look at the transmitted signal of the longitudinal waves. This is a genetic problem, here we have, we consider it as a multilayered structure and I put water there because the water in both the sides acts as a couplant and the energy is transmitted from one side and received on the other side and other layers are suitably labeled there. Layer 5 and 3 are labeled as adhesives. Now when there is no bond or there's an air gap, then what happens to this adhesive layer that instead of the adhesive will have air there, vacuum or air and I will be discussing how that can help us in resolving the disbond problem. Or one can put it in a little bit better fashion, how these layers look alike and there's an incident beam here. I've shown this at oblique angle but I'll be using what is a normal incidence and the other layers are there to receive the signal which is transmitted from the other side and from this received signal we can analyze if there's a bond or disbond present on the wave.

Now if we look at multilayered structure of J-layers, then the input impedance of J^{th} is given by this expression here, it depends upon the impedance of the previous layer, it depends upon the wave vector K_J which is a complex which takes into account the attenuation of the layer and it also depends upon t, the thickness of that layer. Let's discuss these two factors here. The impedance of any layer depends upon the density of the layer and the velocity of propagation in the layer. If instead of the layer, we have air or vacuum then ρ would be approximately equal to 0. In that case the impedance of that layer will be 0. Consequently the signal from that place will be more or less reflected back, there will be very small transmission. That means in the transmitted signal you will not see any signal and that's an indication that there's a disbond somewhere. The other situation can arise when the thickness of the layer is equal to 0 or almost 0. That is the case when we talk of kissing bond. If it's under compression, then the air gap which is present there as you compress it, that will become smaller and smaller. If you look at this expression, when D goes to 0 then the impedance of J^{th} layer becomes equal to J-1 layer as if that next layer was not present there. So what happens in this case? Since it seems the next layer was not present there, the transmission increases. So even though we do not have a real bond there, it's just an intimate contact, the signal increases there and this causes an anomaly which we will discuss.

Most of you are familiar with this, this is from Mistosky's* book of waves in the layered media and the transmission coefficient can be given by this expression for the several layers which I have discussed and the things which I just discussed before that for ρ is almost equal to 0 if you make the analysis, then the transmission of the system, it can be proved, is equal to 0. There's no transmitted signal there. However, under compression it is found that when the delaminations are greater than 0.3 micron, this was done in separate experiments a few years back, then the transmission is 0; however, if the delaminations are less than 0.10 micron then the transmission coefficient can be anywhere from 0 to 1. I will show you some viewgraphs which really indicate these things happening there. So what happens for compression lowers, the gap walls are in contact, that's the case even though they cannot bear a tensile load. So for the purposes of this vibration reducer, we followed this through transmission technique, we had two matched transducers and we found the transmission technique is very convenient and efficient and right now I have an automated system, I just push the button and I see the image coming out so it's very convenient if you have many, many of these to be evaluated. It gives you the digital images which can really show the bond variation thickness and delaminations. The experimental setup is a very standard setup. The part which is very important here that this is all desktop controlled here. You do not touch anything, it's automatically aligned, the software is written for this desktop computer, it's automatically aligned and if you want to change the part, the transducers move out of the way and you replace the part and press the button and the next thing you see is a digital image coming out of the VAX terminal.

Now this was a piston which is to be used in SSN688 and the graph here is really a 3-dimensional graph. We have z and θ, we just unwrap the piston and we see angle versus z and the shade or the color of that gives you the amplitude. If there was no bond there, there will be no signal there or the signal would start reducing, you'll see white spots in that area. Otherwise if this is all very dark or so we say it's a good part and we pass it. Just to show another one of these for class 637 and those little lines you see there, something's wrong with our techtronics plotter there that those are not real things there. Should there be any delaminations present there, this is plotted slightly differently, then we'll see the white spots there. I find that this gray scale is a little bit easier for the managers to look at than the colored scale because you have to look in the chart. If it's white there's a gap there. The thing to be noticed

*Actual spelling may be different than shown

is this feature here, the gap just looks like this here. We took the piston and we cut it open to verify if that was the case. We cut it open in 20 degree sections, pieced the sections together, and photographed it. Wherever there was no bond the rubber peeled off very easily and the pattern looked like this. If we put this one with this one except the scale in the vertical direction is slightly different, you'll notice the pattern is identical there. Every feature has been recorded there. This was before cutting it open, and when we cut it open we do see that. That gives us some confidence that the method does work except for still one problem left to be answered, if there's a kissing bond, then what happens?

We also made some specimens in which these were the same materials, same thicknesses, but made as steps there in one of the specimens there were some defects introduced. The other one did not have any defects and we wanted to see, to validate the procedure, we checked these two specimens with a through transmission technique and imaged the steps. And we found that the specimen which did not have any defect there except for the edges where the signal drops off because it transmits through the water instead of the medium, more or less the bond was very good there. However, if the specimen in which we have introduced artificial defects or so, we did see the debonds there which also gives us the confidence that the method is capable of detecting the disbonds there. The problem which is there is that when the bond is under compression then what happens? So for this purpose we made a jig which looked like this, and that's a piece of rubber, and the rubber was sandwiched between these two big steel plates and half of it was bonded from both sides and other half was not bonded at all. The idea is to apply compression on this with these both and see what happens to the signal as the compression is increased. When this specimen was mounted there it was slightly tilted so you don't see exactly half there, you see sort of an angle view of this. This area was a good bond area and this area where there was gap and there was a slight contact going on here. This was under a tensile torque and as we increased the torque, we see something like this which will indicate that it's bonded all over the place. As you recall from the previous slide, in reality only half of it was bonded and as you increase the compression that means you reduce the gap we see something like this. But we know that half of it does not have any bond, it's just air there except it's in very intimate contact now. What we found here was that if we had put the signal

in the dynamic scale here so though it does not saturate in the bonded region. As you increase the compression naturally the signal will start increasing and the signal gets saturated or reaches to maximum and we see the whole black thing there. The way to overcome this thing, what we do is we put the signal at the low end of the dynamic scale of the amplifier and then repeat the same experiment. So we see that the signal which is there is really this area here. This is slightly tilted from there and you will notice that this area here is not bonded there. Only the signal increased because it got saturated. This area here now also indicates it's not as dark as we had started with in the previous case here and you notice that as the torque there the bond here sheared off. Only this one is left, there's still some medium in that as compared to the air there and this is why this signal is slightly higher than this. But clearly one can from this see which area is bonded and which got sheared off or so. We did one thing more after this and that was we looked at the transmission amplitudes just to make sure that the variation in the material property is not big enough to give us the indication that there's a gap or so. We found that in the materials which we're using for this vibration reducers the variation in the steel is only a tenth of a dB and the rubber is about 1 dB and polyethylene less than 1 dB or so. Whereas if there were delaminations there then we found the signal dropped by almost 25 dB. So this signal could not be because there are variations in material properties. And also we found that under compression if we called that signal a 0 dB then for the air interfaces when we ....(portion inaudible).... signal dropped only by 9 dB, there was still a factor of 1 to 3 there to indicate that we can find there real or kissing bonds.

(beginning of new tape, first part not recorded)

.....transmission analysis is very convenient, we can evaluate the compression effects, we can image the interfaces and we can detect these adhesively bonded components under compression. And the system is completely automated. We had to do about two or three hundred of these which go directly from the lab to the submarine and so we needed that kind of a capability. I am not presenting here with some of these which we saw there were defects there, we did try leaky waves but we can only see from one side what happens and the results were in agreement, the ones which had that disbond there.

Joseph Cappetta
U.S. Army Armament, Munitions and Chemical Command
Picatinny Arsenal
Dover, New Jersey

BOND STRENGTH EVALUATION USING ULTRASONIC SIGNAL ANALYSIS TECHNIQUES

An objective of all of our laboratory studies and workshops such as this should be the practical application of some of these new NDE techniques. This transition from laboratory to actual application of real hardware can be very frustrating. So today I would like to offer some encouragement by showing you some progress made in applying an ultrasonic waveform and feature analysis technique for evaluating bond integrity.* Now our application is on diffusion bonds which is not strictly speaking an adhesive bond; however, there are similarities and we feel that the technique warrants investigation on a wide variety of NDT applications including adhesive bonds. Our application is on the 155 mm atomic projectile and specifically deals with the bond between the copper rotating band and a titanium rocket motor body. Now that bond is considered critical because of the high stresses developed in firing as can be seen, their high engraving stresses and torsional stresses. If that bond should fail we would get a short range or an erratic flight and as a matter of fact, early in the development of this item we did have a major setback because bands were coming off. That problem has been solved once it was discovered that there was an inherent weakness between copper and titanium in diffusion bond. It has been solved by adding an niobium layer however there is still great concern that we assure that we do have a strong bond through process controls and inspection.

The diffusion bond itself is achieved by swaging the copper band over niobium foil and then subjecting the assembly to a combination of high pressure (15,000 psi) and 1500° temperature for four hours. To achieve effective bonds we have tight controls over the diffusion process over the process itself involving cleaning, controlling hip temperature, hip pressure and time. In addition to that, each body is subjected to a nondestructive C-scan pulse echo C-scan from the titanium side and one body per lot subjected to a bend test.

As previously mentioned, many of the speakers have mentioned the limitations of our present inspection methods. The ultrasonic C-scan for instance only shows

*No figures are included with this transcript

intimate contact also referred to as kissing contact. It cannot show that there is in fact a bond or what the strength of that bond is. It does not indicate whether or not there is niobium present. The bend test is destructive, expensive, time consuming and worst of all it cannot be used for 100% inspection.

So what we needed was an inspection system which would be nondestructive, would be sensitive to bond strength and it could be used practically for 100% production inspection. Before we could develop such a system we needed closely controlled test samples. The parameters which we feel affect strength to the greatest extent were both temperature and the presence or absence of niobium. So we made samples at various temperatures. Class 1 were made at the 1500° temperature and passed both bend test and C-scan and we made samples at lower temperatures which were marginal and failed the bend test but yet still passed C-scan and we also made another class without niobium. These were our test samples which as I said were closely controlled to minimize variables.

This is a sample of a good bend test showing no separation between the copper and the titanium. One which failed the bend test showing the distinct separation at the titanium copper niobium interface. These samples were also verified metallurgically showing the difference in the diffusion layer. This is a good sample at 1500° and you see at 1150 the diffusion layer is much less. Using these samples we considered various NDT techniques. We tried proof testing, drop testing, we tried to pull the bands off with an electromagnetic pulse, we tried acoustic emission testing, a simplified version of an ultrasonic spectrum analysis, we used an EMATs horizontally polarized wave.

The only technique which we found which seemed to have promise was the use of a computer analysis of the ultrasonic signal itself. This technique is based on the fact that the ultrasonic signal contains much more information than we generally use. For instance, on our C-scan all we're using is the peak amplitude. Through use of computer techniques now it is possible to analyze the signal in much greater detail. We conducted an initial feasibility study at Sandia Livermore using techniques developed by Dr. Rose and his associates. Encouraged by that we continued an advanced study by Rockwell at the Rocky Flats Plant and this resulted in a contract with Sonatech to develop a prototype production inspection system. The basic schematic of this system, it's IBM PC-based. A 20 MHz wide-band transducer is used in the pulse echo technique similar

to our C-scan. That ultrasonic signal is converted into an electronic signal and it goes through a high-speed A to D converter, stored and processed by the IBM PC using a special software. The software package transforms the RF signal, here we see it, a rectified time waveform, an envelope, an energy spectrum, and then it measures various 24 features of the waveform. For instance it measures peak amplitude, it measures center frequency, it measures frequency at points 6 dB down and up on the energy spectrum and it measures energy in the spectrum between specific frequency bands, for instance band 4, 18.74-25 MHz. Using our samples then we gathered all of this waveform information and we found out there were several signal features which corresponded well to bond strength. This is a plot of some of that data. The good samples, samples 1, 2, and 3, the data from those samples are shown in columns 1, 2, and 3. The two bodies without niobium are columns 4 and 5, and then the low hip temperature weak bonds, columns 6 through 10. I should say that on the low hip temperature bonds, the bonds got progressively worse, bonds 9 and 10 being the worst. So if you look at the peak amplitude you would expect to get more amplitude out of those two but we have marginal bonds here which don't look that much different than the good bonds. The one thing you'll notice throughout here is that those which have the good bonds have fairly tight consistent groups where there are distinct breaks although subtle and more scattering on those which had the poor bonds.

Our next step was to attempt to arrive at accept/reject thresholds based upon this data. Using the five features shown here, peak amplitude, center frequency, 6 dB down upper frequency, and two levels of band information, band 3 and band 4, basically the high frequency bands, we were able to screen our data through these five features and well I'll go through it. If we set a threshold for instance on peak amplitude at 200, we reject the two worst bodies which we would expect and these probably could have been caught on the C-scan also. Basically this is the same thing we do on a C-scan. But you'll notice the marginal ones still get through and the ones without niobium still get through. Now screening out that data we move to center frequency and we're able to now set in a new threshold, we're able to screen out body 6 which represents a low hip temperature bond. The 6 dB down upper frequency feature worked out very well for finding the bodies without niobium and some of the low temperature bonds. Likewise band 4, the high frequency content, was able to screen out the additional remaining bodies without niobium and low temperature. So that when we

subjected our waveforms through this sequential pattern, we were able to accept all of the waveforms from the good bodies and reject virtually all from the ones we considered poor.

The status of our program is that we feel we've shown nearly 100% correlation with bond strength using this feature analysis pattern recognition system. We've built a PC-based system which actually this week is being installed at Chamberlain Corporation and will be used as a 100% screening process. Initially it will be for informational purposes so that we can accumulate a data base but if the data continues as it has been, we expect to be using it for acceptance inspection in Fiscal Year 89.

In conclusion then we found that an ultrasonic feature analysis and pattern recognition technique, we found it to be a powerful new analytical tool for evaluating material properties and importantly it is shown to have practical application for production acceptance testing. We're very encouraged by the initial application of this technique. We would like to promote it, promote this technology and if we can be of any help to any of you in looking into this technique or for your applications, please feel free to contact us.

MORNING DISCUSSION AND CLOSING REMARKS
April 14, 1988

Ron Kline:

I'm going to put in my two cents on the question of strength. I think the whole question of strength may be one which is a little bit ambiguous and not just for the reasons that Jack Duke cited yesterday. The question of strength in an adhesively bonded joint is obviously a very complex one. Even in conventional materials, in a composite, or in an aluminum, or in metals, anything that we usually deal with, we very rarely ask ourselves from a nondestructive testing standpoint to develop a strength measure. Why in the case of an adhesive bond which is extremely complicated, where we have to understand the physics of adhesion, where we have to understand a little bit about chemistry, where we have to understand the fracture mechanics of a viscoelastic material, very complicated situation? Why do we expect that we can come up with a magic single measure of strength with a nondestructive testing technique? I think that's unrealistic. I think that we should be concentrating more on saying whether or not we can detect particular defects. Can we detect deficiencies in primer, can we detect cure variations, can we detect local surface contaminations? I think those things, local changes in morphology of the interface, those are the type questions I think we should really be focusing on and to draw crude correlations between a measure of strength which really, you know you have to quantify in terms or classify in terms of what type of loading conditions you have present and what type of defects you've artificially created at your interface. To draw crude correlations between those strength measurements that you get and an ultrasonic parameter or another NDE parameter I think is very, very misleading and really quite dangerous.

The second point that I want to bring out is in terms of how we model the interface. We seem to be going down the road where we're using a spring model where we're going to say that we're going to assign artificially a shear modulus or a tensile modulus to the interface which we're going to say is different from that of the bulk material. That may be absolutely true but there's no reason, a priori, to expect the stiffness of that material to be any different from that of the bulk material necessarily. All we know is that the strength of the interface is different and there may or may not be a correlation between the stiffness and

the strength. And to artificially say that we're looking for a particular type of modulus variation at that interface I think is another area that we may be adopting a model which may have no bearing on physical reality and may also be a little bit dangerous and misleading.

The final point I'd like to make is there have been a lot of comments saying that well we're going to use interface waves, we're going to use leaky Lamb waves, we're going to use feature extraction, or we're going to use this or that or the other technique, acousto-ultrasonics, whatever, because there really isn't a good technique out there. I believe that 100%, there really isn't a good technique out there. But to say that those are the only techniques that are available is also a little misleading. What we're looking for from an NDT or NDE standpoint, is really some means of qualifying whether or not the material that we create is going to perform its desired function when placed in service. It's not necessary that you have to come up with an ultrasonic technique or something like that to evaluate bond strength. There is another approach that can be taken which has received very little attention during this entire workshop but it's one that GD started for the FAA a while back and that is in terms of conducting a localized proof test. If you can conduct a localized proof test and they were using a technique based upon using high power ultrasound to, at least in theory, to locally fail a poor material and not fail a good material. At least that was the basic premise, that you would have some technique that would allow you to qualify material for service. For various reasons, that program was not successful but I do believe that the approach may be sound and one that deserves a lot more scrutiny than we're paying to it at the present time. The advent of high power lasers are becoming available to us in the laboratory as well as in production ultimately. I think that this offers the opportunity to generate the types of stresses that you need to actually conduct a localized proof test. Obviously it's not going to be a nondestructive test, it's going to semi-destructive but at least in principle the potential is there to address many of these concerns in a truly unambiguous fashion and I think that that area is an area that has a lot of potential which people are really overlooking right now in my opinion.

Speaker not identified:

I would like to make a comment if I may about the question you raised because it's a very important one. The only thing that I can think of is that the customer who in this case many times might be an industrial plant or quality control manager may feel it very important for him to know the strength of the bond say, and someone has to take the risk upon himself to say well if I can tell you whether the cure is right or whether there are flaws there, then I can tell you how strong it is. Even though he may not be able to build a theoretical model to justify that he, that is the NDT purveyor, has to assume that risk because in my case, in the automotive industry the QC manager is not going to assume that risk and therefore if you want the job of developing a method to do the NDT, you have to assume that risk. And I guess that's fair because when people sell cars or rockets, it's the producer who assumes the risk and not the customer.

Ron Kline:

I guess the only thing I have to say to that is sure, we'd love to be able to do that but is it realistic really to do that with what we know about the material performance today. We don't know enough about fracture mechanics to do that in a polycrystalline metallic sample, how can we do that in a bonded joint.

Speaker not identified:

That's why I call it assuming a risk.

Speaker not identified:

Along somewhat the same lines I think your point is well taken. Why do we demand that we be able to specify a risk for these joints where we don't necessarily for other more conventional materials. I think it's basically the issue that these are new materials, they are new technologies in the case of adhesive bonding or at least in application to high tech systems and as much as anything, it's a matter of convincing designers that they can take the risk of

using these materials. Hal Brinson yesterday attributed to the fellow from Fokker Aircraft the statement that if you can't inspect it, you can't fly it. That's what we deal with. We've got to instill a level of confidence, in this case we're trying to quantitate the strength figure. Maybe if aluminum came along today we'd have people demanding that same kind of criterion be applied to it.

Ron Kline:

Now those are two different questions. A level of confidence, certainly we can address that from a nondestructive testing standpoint. Can we at least in principle assure that the material is going to perform adequately. But to actually assign a number to what that strength may be in practice, we might have to be forced to settle for range of strength. Can it be a certain limit, now that may be something that's realistic. But to actually assign an actual value for strength I think may be very difficult.

Speaker not identified:

It looks like the question of strength is like opening a can of worms. There is no question that there is a stress field at the interlayer in strength usually, like if you extrapolate what you have done for metals is defined or precisely when you have a uniform state of stress. However not looking at it and not trying at least to define a parameter is forgetting one of the primary purposes of a bonded joint which is to carry loads. So even though there is some degree of impreciseness, and I agree with Kline, I think it's very important that we don't lose sight of one of the primary purposes of a joint load. So that's to carry load, another is to dissipate energy or whatever, but it's an important parameter to use and for lack of a better one, why not use it.

Speaker not identified:

I've got a question for Joseph Cappetta, but before I put that question

forth I would like to make some comments regarding the current issue, whether or not bond strength should be a measure of how well we can transfer load from one adherent to the other. Yesterday, Robert Bonk presented a couple of slides. He showed that what the Navy, Army and Air Force are interested in is how well we can transfer load from one material to the other through an adhesive and that is the qualitative definition of the goodness of a bond or the adhesive. Now that particular criteria he showed could be described in terms of several parameters and bond strength is probably just one of them. So what the customers are interested in is not probably directly describable in terms of just one parameter named the bond strength. Robert Bonk went on to describe how these different parameters could be measured by different means and I think his slides should be a starting point for different nondestructive methods of identifying the parameters. That is my comment and my question to Joseph Cappetta is that he is using five parameters, how well can you use these parameters to discriminate between say thickness variation and debonding, etc.

Joseph Cappetta:

I assume you're referring to adhesive type bonds. I presented one application, it's diffusion bond. We're looking for two things with this technique as I mentioned. We're looking for features related to the hip temperature which are related to how much fusion takes place and we're looking for the presence of that niobium layer. To test this technique for other applications you would have to make samples which represent what you consider good and bad and subject it to the same type of test and then determine which features best separate your samples. Now I think we may have come close to what you're asking for in detecting that niobium layer, because that is an additional thickness of material there. We could not detect it using the conventional C-scan because it looks like one surface, but when we looked at the high frequency features we were able to very clearly detect that that thickness was there so that particular feature may work well in that application but for any application you're going to have to make your samples and then test them and find out which features work the best.

Speaker not identified:

I would like to make a couple of comments on what Dr. Kline had said before. The first is I'm concurring with him that at present we are not probably able to figure out a quantitative sense of strength of a bond but as is evident from the last few papers, we are in a position to probably say in a qualitative sense what happened during a bonding procedure by a direct correlation of some ultrasonic or NDE quantity correlated to how the bond, or like for instance, what is the degree of cure or was there a thin film and so forth. Right now I think probably the industry will have to somehow figure out how to use such information and predict the performance of a bond because I think the reason for the necessity of strength of a bond in a quantitative sense is to predict what is the performance of a bond. There is probably no way you can at the present time. We can probably give a quantitative evaluation, but in a qualitative sense, information can be provided and it has to be used in the best possible fashion.

The second comment which he made on the interface model, I have to defend it because I have used it. The interface model is built on a physical basis. We are trying to model the interface not to springs, it is just the way it is represented. We model it on the basis of the primer material and we think the primer material has like any other material certain elasticity in different directions. The only thing we try to do is we kind of vary the Poisson ratio of this elastic material or the primer raterial at the interface and the best way to represent it is by using the spring model. I think there is a certain physical validity of this model.

Speaker not identified:

I guess I would like to disagree slightly with that last comment. I think the only real values that we have to characterize that particular interface come from some work at Lockheed in California where they are doing sectioning of the sample and looking at critical angle for Rayleigh wave incidence and from those measurements it looks like the principle effect is going to be an interfacial combination zone where there in fact is a transition region where the shear modulus varies continuously through the transition region. That may be a more appropriate means of modelling that. To say that the transition region

characterization parameter should be the modulus of the primer I think is a gross oversimplification of really what's going on at that interface.

N.K. Batra:

In answer to your second comment maybe I'm not so sure about it, but the way it is we are looking at ultrasonic wavelengths comparable with probably thickness of the bond and so forth and definitely much, much larger than that of the interface. So if we are going to try to model an interface with changing gradients of spring model or a gradient of properties and so forth, aren't we really going too deep into the problem? Overkill or something?

Ron Kline:

Not necessarily. If the dimensions of these IAZs as they're called are roughly on the order of the wavelength at 1 MHz in aluminum, something like that, like 0.2 mm along those lines. So it's not unrealistic to expect that we can probe those regions with conventional ultrasonic techniques if we know what we're really looking for.

N.K. Batra:

The interface which we dealt with was of the order of microns so in other words, our bond was of the order of 0.1, 0.2 mm but the interface between the primer coating and so forth are of very small magnitude.

Ron Kline:

That brings up another question. Why a priori would you expect a strong interaction between an ultrasonic wave whose wavelength is much larger than the dimensions of that interface?

N.K. Batra:

Well, that is the influence of the bond recondition.

Ron Kline:

I'm not convinced.

Speaker not identified:

Let me elaborate a little bit more on what I see is the need for strength determinations. As important as it is in quality control, it is crucially important for in-service monitoring. Again the issue if you can't inspect it you can't fly it. For metals you can inspect, you can look for surface flaws, for an adhesive joint you cannot. It would be highly beneficial to know how much the strength, at least semi-quantitatively has degraded in-service so you know whether or not it's getting close to the time to withdraw the structure and replace it or whether or not having exceeded the conventional or nominal useful life you can still safely continue to use that structure. The economic impact of this is really quite significant for the military.

Ron Kline:

Well I never said that strength wasn't an important parameter. I just didn't think that we could quantitatively measure it to any accuracy that people would be comfortable with. That was only my point. I think it's certainly a goal of all nondestructive testing to be able to establish the strength. It's not just a nondestructive testing problem. It has to do with fracture mechanics and things like that as well. My only point is the question, how realistic is that question to begin with. That was really the whole point of my comment.

Speaker not identified:

I'm kind of confused at why should you expect from nondestructive means a parameter which is a destructive parameter.

Ron Kline:

Good point.

Speaker not identified:

Another comment which I want to make is that at present with the bonds we are faced with this problem which is very important and that is the variation in thickness of the bond, whether it's a good bond or a bad bond and put some qualitative numbers on that but to expect that how it will perform after it has been made depends on the external conditions also. A priori if I have a rubber bonded piston and they come to me and say that, hey should we change it after 5 years or 2 years. All I can tell at this time the bond is good and after that it depends on what kind of environmental conditions this is used in and if there's a variation in the temperatures or other things, you cannot put a number on it. Even if you can give them the strength, you cannot give the lifetime then after that. So these are the problems which really speaking fracture mechanics should be solving, not NDE community.

Speaker not identified:

Coming back to what you just said also reinforces the need for NDT. As you make a part, at that point you have basically quite a bit of information. How much you can have as a part is being used you start losing information. People use reliability theory to all kinds of things, but it gets to a point that you have to assess again the integrity of that part and you don't want a destructive test. You want some technology called NDT that goes there and gives you back that information that you lost through the time. That's why our roads are in bad condition, our bridges are in bad condition, they don't know how to inspect that. So there is a need to again regain that information that you lost the past 22 years of service.

Speaker not identified:

I think one area that we can look at is the use of NDT as a form of process

control. I think when it comes to bonding the thing that controls whether or not you've got a good bond is whether or not you've followed the right process. For instance, we've found with this feature analysis technique that it can tell us when the process is changed, when something is different in that process whether it be temperature, whether a part has been left out, or cleanliness is affected. It will show differences in the signal so while it may not show us exactly what the strength is, it could tip us off that something has happened in the process which could affect the bond.

Speaker not identified:

I'd just like to reinforce what Mr. Cappetta is saying because I think that he's gotten into an area, I'm quite pleased to see that he's developed a production application out of, it's an area that's going to be very strongly growing in the field of nondestructive evaluation in the next several years. In fact the leading edge work in this technology is just coming out, systems are being developed, and you'll see an increasing influence of these systems on automated inspection in the future. There's probably a lot of useful information in standard NDT techniques which we overlook simply because we don't have with our eyes the ability to see all the information that's there. We may find ourselves rather than designing new NDE techniques going back to the ones that are fairly standard like a simple pulse echo examination and looking for more information in that signal which is relevant to different defects or bonding conditions in a particular situation. Where you have some knowledge of the range of defects or conditions that exist and those are let's say limited in an unlimited sense, you can define those as classes of problems and if you can get enough of the good types of samples of those to teach a computerized system what those classes of signals look like, you can develop a very reliable inspection and the numbers I've heard thrown about are pretty typical of our own experience. Some are in the range of 95-98% correct identification of bond or defect or some other kind of condition is realistic to expect with a properly trained classifier. We're rapidly getting to the point where automatic feature extraction and optimized classifiers for doing this on-line in a PC-based system is a reality. You may see within a year or two on-line systems that make those decisions within tens of milliseconds of having digitized and received a signal.

I just want to reinforce that you're going to be seeing a lot more of this work and I'd like to congratulate you in achieving this breakthrough and putting it into a production environment. It certainly is an accomplishment I think.

Speaker not identified:

If I may comment on his statement here. Feature analysis and feature extraction is an excellent tool for an industrial environment and definitely is a big plus point in investigating any material. We have had sufficient experience with feature extractions and the basic philosophy under which it works is the fact that you extract features, in other words you extract information which is there. This is the most efficient way of extracting information or of any signal. But if there is no information in the signal there's no way you can extract anything out of it. So in that situation you have to look for other techniques and this is a very excellent complimentary tool which we can use in the inspection. But we have been forced in the past to look for other techniques where there is sufficient sensitivity.

Speaker not identified:

We've heard a lot about the issue of good bond and I think a lot of times that's used to be synonymous with strong bonds. I'm interested in knowing if those who are here in the most recent part or perhaps others who have spoken can address the issue of good bond versus good bonding. It's kind of like the composite material not really being a material but a structure. The adhesive bond is not really a point but oftentimes there's a surface. If you have a poor or a weak bond over a large area it may be a stronger joint than if you have a very good or strong bond in a very small region. So the issue of strength becomes one of both bonding and strength of bond and getting back to the issue of the differentiation between those features are also the differentiation between stiff and compliant bond as well because there's a great deal of concern about controlling and understanding interfacial properties and it's not just a matter of being able to substantiate the strength. If the properties of the interface are not what you want, what do you do when you go back to talk to the chemist or

the adhesive bond specialist, what do you tell them? You tell them it's a good bond and they say well does that mean there was a lot of bonding, it wasn't stiff enough, it wasn't ductile enough, can somebody address some of those issues which are a little bit muddled together, good bond versus good bonding, stiff bond versus strong bond, weak bond versus no bond.

Speaker not identified:

I think there are a couple of issues here. First off, good bond in the sense that I'm using it means a bonded structure that is capable of performing it's function over a specified period of life. The issue of whether there's a bond there at any given point or not I think Dr. Bar-Cohen covered pretty nicely yesterday especially with the lap shear specimen. No bond in the middle is of no consequence whatsoever. You've got to have the good bond in the right place and with regard to strength versus goodness and so forth, I guess that's why you've got to go all the way back to the initial design phase and design for an adhesive joint from scratch and not design it for mechanical fastener which is a classic example of a very good bond in a very localized region that has a lot of problems associated with it. You have to go back and design for an adhesive joint from scratch.

George Matzkanin (closing remarks):

I think if there's one thing that I learned from this Workshop is that I, I was going to say maybe I made a mistake in using the word strength in the title, but maybe I didn't. It seems like it spurred a lot of discussion. There clearly are a number of issues that need to be addressed in this particular area. I don't think there was any intention that they would be solved during this day and a half and as Bruce Thompson pointed out yesterday, this particular area, this particular question of nondestructive determination of bond strength, quality, integrity, whatever you want to call it has been around really for a number of years, it kind of goes up and down. It was really popular about 10 years ago and then it kind of dropped off into a valley and I think now we're picking up interest in this area once again. I think one of the things we need to be

careful about is that we don't spin our wheels to the extent that we're going over material that's been covered and was covered maybe 10-15 years ago. I was discussing briefly with Don Thompson yesterday the fact that they may try to pull together some of the information that had appeared in some of the NDE conference proceedings over the last 10-15 years that bear on this particular subject, perhaps collect that together into a single document and if something like that does become available within the next year or so I'm sure that will be of interest to many here. Also as was pointed out yesterday we are working on a state-of-the-art report dealing with, again, specifically on the nondestructive evaluation aspects of this particular problem. Clearly there's a lot of information associated with the mechanics, with the chemistry, and other aspects of this particular problem and I really think that it is a very interdisciplinary problem that we are going to have to pull forces together from a number of different factors. I would like to thank everybody again for being here. We will be putting out a report that we hope will summarize much of what was presented and discussed at the Workshop, we hope to have that done I would say by, let's say, I'll stick my neck out and say the end of June, sometime this summer. It takes a little while to pull this information together as many of you know. We also will be sending out an attendance list to those who are here. We probably will have that done this next week. Thanks again.

Paul Kenny:

Okay, so in the vane of the Oscars I'd like to thank a few people. The secretary, Maureen Ahr out front who did all the typing, nametags, collecting the money, I'm sure that was fun. The audio guy Bruce over here, he's been here recording the last day and a half. He's done a very excellent job of keeping control of the mikes and not having too many feedback problems or anything like that. Richard Cervantes in the back who handled the lights, some of the video-type stuff. I'd also like to thank George Matzkanin who for well over a year has really worked hard pulling this Workshop together. Most of all thanks to all the speakers and participants who without you guys this wouldn't have been possible and I don't think it would have worked out as well as it did. I believe it was a very successful Workshop and I thank you. Meeting adjourned.